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Water Quality Studies: Hartwell Lake 1993-1994 Summary Report

by William E. Jabour, WES
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Prepared for U.S. Army Engineer District, Savannah

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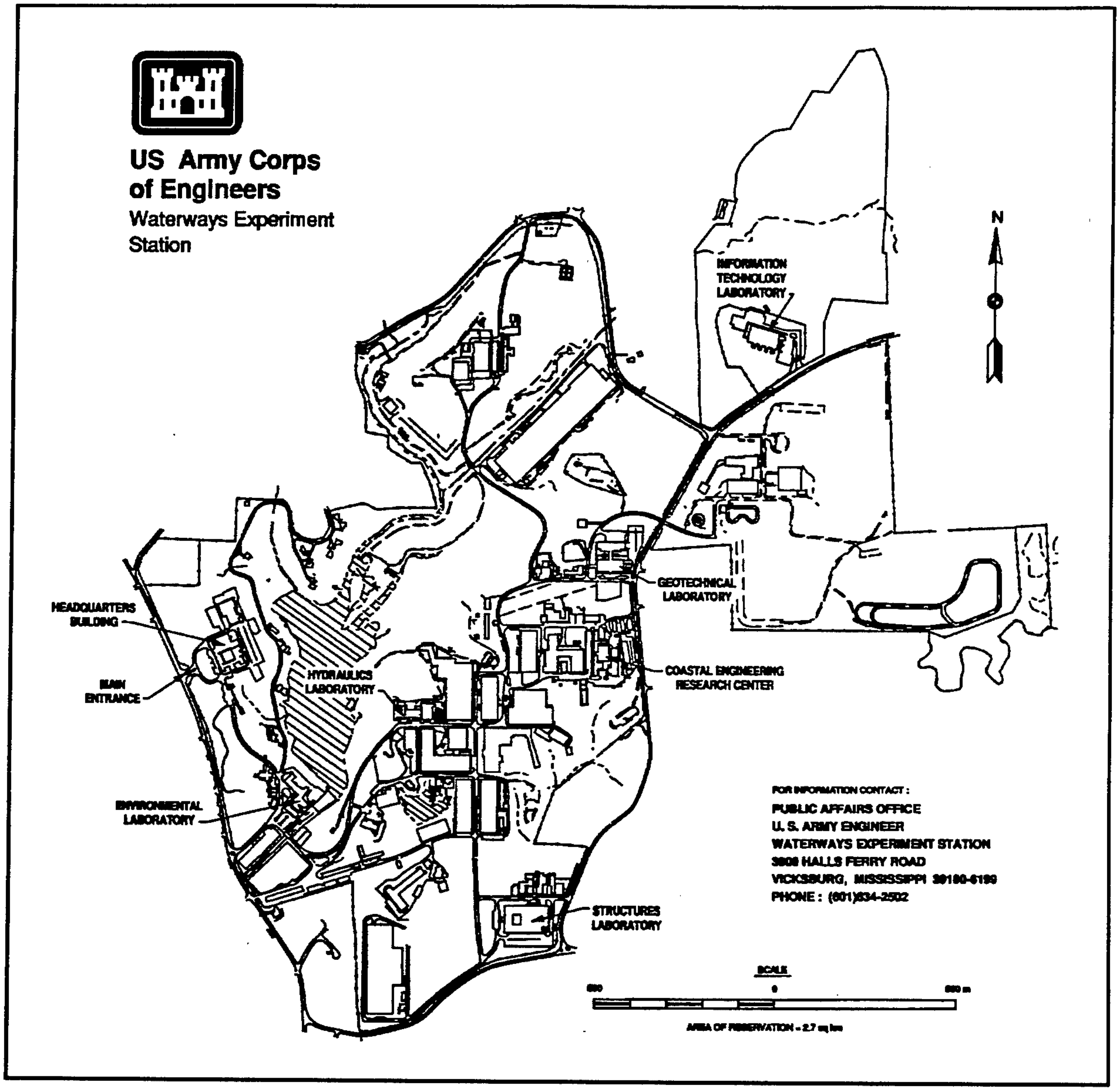

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Contents

Preface

Water quality studies at Hartwell Lake continued in 1993 and 1994 as a cooperative effort by the U.S. Army Engineer District, Savannah, and the U.S. Army Engineer Waterways Experiment Station (WES). This report, which covers the period April 1993 through December 1994, is the third annual report summarizing study results.

The Principal Investigators for this work were Dr. Robert H. Kennedy and Mr. Joe H. Carroll, Ecosystem Processes and Effects Branch (EPEB), Environmental Processes and Effects Division (EPED), Environmental Laboratory (EL), WES. The report was prepared by Mr. William E. Jabour, EPEB, and Mr. Mark Satterfield, Computer Services Corporation, which is now the DynTel Corporation, Vicksburg, MS. Field and technical support were provided by the following Trotter Shoals Limnological Research Facility personnel: Mr. Carroll, Dr. John J. Hains, Mr. Jabour, and Mr. Mark Gunter, EPEB; Dr. Edward Robertson, Ms. Cynthia H. Penland, and Ms. Kim O. Jones, AScI Corporation, McClean, VA; and Mr. Michael C. Vorwerk, Mr. John Lemons, Mr. Satterfield, and Ms. Deborah Patterson, DynTel Corporation.

Additional assistance was provided by Messrs. Steve Mason and Kenneth Bedenbaugh of the Hartwell Lake Resource Management Office, under the supervision of the Resource Manager, Mr. Dick Austin. Technical reviews of this report were provided by Drs. Kennedy and Hains.

This investigation was performed under the supervision of Dr. John W. Keeley, Director, EL; Mr. Donald L. Robey, Chief, EPED; and Dr. Richard E. Price, Acting Chief, EPEB.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

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1 Introduction

Hartwell (HW) Lake, completed in 1962, is a U.S. Army Corps of Engineers impoundment located on the Savannah River along the Georgia/ South Carolina border. HW Lake has a surface area of 22,400 ha and provides hydroelectric power production, flood control, water supply, and recreational usage. HW Lake is one of the top three most visited Corps of Engineers lakes in the nation, attracting 14 million visitors annually. Water quality concerns at HW Lake, including formation of hypolimnetic anoxia and its effects on lake and release water quality and fish distribution, were addressed during 1991[1] and 1992.[2] These investigations continued during 1993 and 1994. Major objectives were as follows:

a. Describe longitudinal water quality trends from the forebay region into the upper Seneca River tributary embayment during both the stratified (spring-summer) and mixed (late fall-winter) periods.

b. Compare and contrast temporal water quality trends of the near-dam stations (depth > 30 m) with those in the Seneca River embayment (depth ≤ 30 m) during both stratified and mixed periods.

c. Assess the onset, formation, progression, and extent of hypolimnetic anoxia through HW Lake during the study period.

d. Monitor release water quality in the Richard B. Russell Lake headwaters through monthly forebay and continuous tailrace sampling at HW Dam.

e. Provide recommendations regarding current and future water quality sampling on HW Lake for the purpose of documenting lake and release water quality conditions.

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1 Jabour, W. E., and Carroll, J. H. (1993). "Water quality studies: Hartwell Lake 1991 summary report," Miscellaneous Paper EL-93-20, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

2 Huffstettler, C. J., and Jabour, W. E. (1993). "Water quality studies: Hartwell Lake 1992 summary report," Miscellaneous Paper EL-93-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

This report documents the results of in situ water quality studies performed in HW Lake during the period April 1993 through December 1994. Presented in this report are summaries of water quality conditions observed during HW Lake monthly sampling trips.

2 Study Site Description

HW Lake was completed by the U.S. Army Corps of Engineers in 1962 as part of a comprehensive water resource development plan for the Savannah River basin. Located along the boundary between Georgia and South Carolina, HW Lake is a very popular multipurpose project, attracting high visitation, particularly during the summer months. The lake has a surface area of approximately 22,400 ha, a shoreline of 1,530 km, and a drainage area greater than 5,400 km^2. HW Lake extends approximately 79 km from HW Dam to Yonah Dam on the Tugaloo River and 66 km to Keowee Dam on the Seneca River. The confluence of the two river embayments forms the Savannah River. This confluence is located 11 km upstream of HW Dam. HW Lake is located immediately upstream of Richard B. Russell (RBR) Lake, completed in 1984, and provided approximately 80 percent of RBR Lake annual inflow during 1993 and 1994. At normal full pool elevation (201 m National Geodetic Vertical Datum (NGVD)), mean depth and maximum depths are 14 and 55 m, respectively.

HW Dam is an earthen and concrete structure extending approximately 5,440 m across the Savannah River. The concrete section is 570 m in length and 61 m in height above the riverbed. The powerhouse contains one 80-MW and four 66-MW generators, providing a total rated capacity of 344 MW. Average annual output is 453,000 MW-hr of electricity. Average outflow from HW Dam in 1993 and 1994 were 140 and 118 m^3s^{-1}, respectively. HW Dam is a peaking hydropower project, with generation dependent on regional power requirements and consumption.

3 Methods and Materials

Routine in situ sampling was conducted monthly from April 1993 through December 1994, with the exception of January 1994. Temperature, dissolved oxygen (DO), specific conductance, and pH were measured as a mean to describe temporal and spatial patterns of water quality from the forebay of HW Dam to the upstream Seneca River (SR) embayment on HW Lake. Data were not collected on the Tugaloo River embayment.

The locations of nine sampling stations in HW Lake and tailrace are depicted in Figure 1. Sampling crews conducted routine in situ monitoring of temperature, DO, and conductivity using a Hydrolab Surveyor 3 Data Logger and H20 Datasonde (Hydrolab Corporation, Austin, TX) at two-meter intervals from the surface to one-half meter above the bottom at each lake station.

HW Lake tailrace in situ data (temperature, DO, pH, and conductivity) were collected hourly at Station 200 using a Schneider RM-25 monitoring system (Schneider Instrument Company, Cincinnati, OH) from January through September 1993. That system was replaced with a Hydrolab H20 system during October 1993, and data were collected using this instrumentation from October 1993 through the present. During the stratified period, each monitoring system was calibrated weekly using standard methods.[1] Calibration was performed bi-weekly during the mixed period.

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[1] American Public Health Association. (1992). *Standard methods for the examination of water and wastewater*. 18th ed., Washington, DC.

4 Results

Hydrological Data

Precipitation, pool elevation, mean daily inflow, and mean daily outflow for the period 1993-1994 are shown in Figure 2. These data were provided by the U.S. Army Corps of Engineers, Savannah District. Rainfall accumulations in 1993 were greatest (20 cm per month) during January and March. Minimum precipitation amounts for the year occurred during June, July, and August, when precipitation averaged 6 cm each month. Rainfall accumulations in 1994 were greatest during the winter and summer months, averaging 20 cm during January, February, March, June, July, and August. Minimal amounts (10 cm or less) were recorded during April, May, September, November, and December 1994.

HW Lake pool elevation was at or above full pool (201 m NGVD) during winter, spring, and early summer 1993. Pool level declined from August 1993 through February 1994, when elevation reached a minimum of 199 m NGVD. Heavy summertime rainfall during 1994 resulted in pool elevations averaging 201.5 m NGVD from May through October.

HW Lake inflows and outflows reflected similar patterns with maximum levels occurring during January through May 1993 and August through November 1994. Inflow discharge rates greater than 260 m^3s^{-1} were recorded during January and March 1993 and August 1994. Outflow discharge rates greater than 250 m^3s^{-1} were recorded in February 1993 and August 1994. Due primarily to unseasonably high rainfall during August (greater than 26 cm), HW Dam average discharge during August 1994 was 270 m^3s^{-1}. These high discharges were accomplished through periods of continuous generation and tainter releases. Minimum discharge rates (75 m^3s^{-1}) were observed during the winter of 1993-1994.

Spatial Water Quality Data

Temperature, DO, and specific conductance patterns for HW Lake during 1993 were characterized by longitudinal, vertical, and seasonal variability. Figure 3 depicts temperature, DO, and specific conductance conditions at the

time of the initial sampling in April. Measurements of pH were 7 ($\pm$ 1) on HW Lake throughout the year. The onset of thermal stratification and hypolimnetic oxygen depletion was observed during April. Surface-to-bottom temperatures were 15 °C to 8 °C in the forebay (Station 210) and 18 °C to 14 °C in the farthest upstream station (295). Upstream temperatures were influenced by warm runoff and shallow column depth. Lakewide surface DO concentrations averaged 11 mg/ℓ. Bottom-water DO concentrations ranged from 9 mg/ℓ in the forebay to approximately 6.5 mg/ℓ in the mid- to upper SR embayment. Conductivities averaged 30 μS, with the exception of the upper Seneca embayment where measurements of greater than 70 μS were recorded.

During May, surface temperatures increased to nearly 25 °C (Figure 4). Uplake bottom waters warmed to greater than 14 °C, while forebay bottom temperatures remained near 8.5 °C. Surface DO concentrations were greater than 8 mg/ℓ, and bottom-water concentrations ranged from 7 mg/ℓ at HW Dam to 2 mg/ℓ at Station 290 in the SR embayment. Hypolimnetic oxygen depletion was reflected in specific conductivity, with concentrations greater than 120 μS recorded in the embayment bottom waters.

Figure 5 depicts the extensive, well-established thermocline present by mid-June. Temperatures ranged from 28 °C at the surface to 9 °C in the bottom waters of the forebay. At the stations farthest upstream, bottom waters were 20 °C. Anoxia was initially observed during June in the bottom waters at Stations 270 and 290. DO concentrations in the hypolimnion of near-dam stations were greater than 6 mg/ℓ. Conductivity reflected spatial variability, averaging 30 μS in the deep-water stations and increasing significantly within the upper SR embayment, where conductivity was greater than 100 μS. The apparent decrease in specific conductance from May to June may have been the result of an omission of a bottom-water reading during June at Station 290.

Typical midsummer stratification patterns were observed in HW Lake during July and August. Surface temperatures in HW Lake in July reached maxima of greater than 30 °C (Figure 6) and decreased to approximately 28.5 °C in August (Figure 7). Bottom-water temperatures exhibited great variability during this period, with temperatures greater than 20 °C at upstream stations and less than 10 and 12 °C in the HW Dam forebay during July and August, respectively. Oxygen depletion continued within the HW Lake hypolimnion, expanding vertically and longitudinally downstream. A plume, or layer, of anoxic water 12 to 24 m in depth, with oxygenated water above and beneath, was observed in July at Station 250, a midlake sampling point. Stations 270 and 290, located just upstream, were anoxic below 10 m. DO concentrations in the lower hypolimnion of mainlake stations had decreased to less than 3 mg/ℓ by August. Conductivity values in the upper SR tributary embayment increased to greater than 150 μS, and a downstream progression of increased conductivity was observed during August.

Surface temperatures decreased to 27 °C in September (Figure 8). The HW Dam thermocline deepened to 14 to 20 m. Bottom-water temperatures

ranged from 11 °C in the forebay to nearly 25 °C at the uppermost SR station. Minimum lakewide DO concentrations were observed during September. From Station 230 near the confluence of the Tugaloo and SR embayments upstream to Station 290, DO concentration was less than 0.5 mg/ℓ at depths greater than 14 m. Anoxia at forebay Station 210 was limited to depths greater than 45 m. Maximum conductivity values for 1993 of nearly 300 μS were recorded at station 290 in the upper SR tributary embayment. Stations immediately downstream reflected a middepth increase from approximately 35 to 75 μS as the region of oxygen-depleted water progressed longitudinally. Bottom-water conductivity values remained approximately 35 μS.

Seasonal cooling occurred during October, November, and December on HW Lake. Surface water temperatures in mid-October decreased to 23 °C throughout the lake (Figure 9). Stations 290 and 295 exhibited thermally mixed conditions. A thermocline depth of 22 m was observed at stations deeper than 30 m. Destratification progressed rapidly during November, when surface temperatures decreased to less than 15 °C (Figure 10) and was complete by 30 December (Figure 11). Vertical gradients in DO concentration ranged from extreme in October to nonexistent by December (Figures 9-11). DO concentrations at Stations 290 and 295 in the upper SR embayment increased surface to bottom during October and mixed by November. October DO concentrations were 1 mg/ℓ or less at depths greater than 22 m. Mixing during November deepened the 1-mg/ℓ layer to depths greater than 34 m and increased DO concentrations to 7 mg/ℓ or more at depths less than 30 m. DO concentrations were 9 mg/ℓ throughout HW Lake by late December. Conductivity values of between 100 and 200 μS were recorded in the bottom waters of the lower SR tributary embayment and the middepths of Station 250 during October. Conductivity increased to greater than 50 μS only at depths greater than 35 m during November. Maximum conductivity values of 80 μS were recorded in the bottom waters of Stations 240 and 250, upstream of HW Dam. By late December, conductivity averaged 30 μS lakewide.

In situ sampling resumed in 1994 on HW Lake on 17 February. Isothermal conditions existed throughout, and temperatures averaged 7 °C (Figure 12). DO concentrations were at saturation, with all measurements between 10 and 11 mg/ℓ. Specific conductance ranged from 30 to 50 μS lakewide.

The onset of stratification occurred in March and April. While surface temperatures averaged only 11 °C in March (Figure 13), seasonal warming had increased the surface temperature to 18 °C by April (Figure 14). Bottom-water temperatures at the deep-water stations remained at 8 °C until May. Surface-to-bottom DO concentrations were 11 to 9 mg/ℓ during March. Surface DO concentrations were 9 mg/ℓ in April, and oxygen depletion was underway in the midreaches of the SR tributary embayment. Bottom-water concentrations were less than 5 mg/ℓ at Station 270. Measurements of specific conductance reflected mixed conditions in March, averaging 30 to 40 μS.

Distinct gradients had developed by April. While surface waters averaged 30 μS, a maximum of 80 μS was recorded in the midcolumn of Station 290.

Late spring-early summer stratification patterns were observed in HW Lake during May and June 1994. Surface temperatures increased to greater than 22 °C in May (Figure 15) and greater than 26 °C in June (Figure 16). Bottom waters in the HW forebay remained less than 10 °C during both months. DO concentrations decreased to less than 1 mg/ℓ in the upper SR embayment during May. Oxygen depletion expanded both vertically and spatially during June to include nearly all of the SR embayment greater than 20 m in depth. Conductivity values during these months increased to near 125 μS, with maximum recorded at 16 m at Station 290 in the upper SR embayment.

HW Lake exhibited typical midsummer characteristics of increased water temperatures and increased hypolimnetic anoxia during July, August, and September 1994 (Figures 17-19). Maximum surface temperatures of 29 °C were recorded in July, cooling to 27 °C during August and September. Bottom-water temperatures in the upper SR tributary embayment warmed rapidly during the summer, increasing from 20 °C in July to 25 °C by September. Bottom-water temperature in the forebay of HW Lake increased more slowly, from 10 to 12 °C during the 3-month period. Surface DO concentrations averaged 8 mg/ℓ during July, August, and September. While anoxia remained in evidence in the hypolimnion of the mid- to upper SR embayment throughout the summer, DO concentrations less than 1 mg/ℓ were recorded as far downstream as Station 250 during July, Station 240 during August, and reaching HW Dam at depths greater than 30 m in September. Maximum monthly conductivity values remained greater than 100 μS during the summer months; however, the greatest measurements revealed a downstream progression from the upper SR embayment in July to near its convergence with the Tugaloo River embayment by September. Midwater column conductivity values of 50 to 60 μS reflected a similar trend.

Seasonal cooling and reaeration during October, November, and December resulted in destratification and an increase in DO concentration in HW Lake. Surface temperatures decreased to less than 22 °C by October (Figure 20), less than 19 °C by November (Figure 21), and less than 16 °C by December 1994 (Figure 22). The SR tributary embayment had mixed by 17 October. Forebay temperatures were mixed to a depth of 38 m. The mixed layer deepened to 46 m by November, and HW Lake mixed completely in December. Forebay bottom-water temperatures remained between 13 and 14 °C from October through December. DO concentration in the deep-water stations were less than 1 mg/ℓ at depths greater than 38 m in October. Anoxia was restricted to depths greater than 45 m during the November sampling. Reaeration was near complete on 7 December. Specific conductance followed patterns similar to DO during the final 3 months of 1994. The SR tributary embayment exhibited mixed conditions as early as October, with conductivity values ranging from 30 to 50 μS. In the bottom waters of the deep-water stations, increased conductivity values greater than 100 μS, coincident with

anoxia, were recorded in October and November. HW forebay conductivity by early December was greater than 50 μS only at depths in excess of 50 m.

Temporal Forebay Water Quality Data

Temperature, DO concentration, and specific conductance at Station 210 in the HW Dam forebay reflected seasonal variability during 1993 and 1994. Gradual warming of the forebay water column was underway by the initial sampling trip (15 April 1993; Figure 23). Surface temperatures increased from near 18 °C in April to a maximum of nearly 30 °C in July. Autumnal cooling during September through November decreased surface temperatures to approximately 15 °C. HW Lake mixed completely by late December with an average water column temperature of 11 °C. Temperature reached a minimum of 7 °C during February 1994. Stratification was reestablished by May, as surface and bottom temperatures were 20 °C and 9 °C, respectively. The maximum recorded temperature for HW Lake in 1994 was 28 °C during the August sampling effort. The onset of autumnal cooling decreased surface-water temperatures to 20 °C in October and 16 °C by early December. Hypolimnetic water temperatures were less than 10 °C in April and warmed through November, increasing to a maximum of 14 °C in 1993 and 16 °C in 1994. Thermocline depth, observed initially at 6 m during May of each year, deepened to 22 m in October 1993 and September 1994.

Surface DO concentrations maintained an average of 8 mg/ℓ throughout 1993, increasing to a maximum of 11 mg/ℓ during February 1994 at Station 210 (Figure 24). Anoxia developed in the hypolimnion during September of each year and remained through November. By late December 1993, the HW Lake forebay mixed completely. By early December 1994, gradients were still in evidence at depths greater than 40 m.

Specific conductance exhibited little variability during the majority of 1993 and 1994. Conductivity values of approximately 30 to 40 μS were recorded surface to bottom from January through August (Figure 25). Conductivity values increased in the forebay bottom waters during September through November, attaining maxima of approximately 65 μS in November 1993 and 100 μS in early December 1994.

Release Monitoring Data

Trends in temperature and DO in the HW Dam tailwater during 1993 and 1994 reflected seasonal variability in the HW Lake forebay. Release temperatures increased from a minimum of approximately 9 °C in March to a maximum of 18 °C in October during 1993 (Figure 26). Release temperatures during 1994 ranged from 8 °C in early February to nearly 22 °C by late September (Figure 27). An abrupt increase in temperature in late August

1994 was the result of surface water being spilled through tainter gates in response to flood conditions.

Maximum DO concentrations were 12 mg/ℓ during mid-February through March in 1993 and 11 mg/ℓ for the same period during 1994. Summer DO concentrations in 1993 and 1994 ranged from 9 mg/ℓ in June to 2 mg/ℓ during September. By late December of each year, lake mixing and reaeration had increased release concentrations to approximately 10 mg/ℓ.

5 Summary and Discussion

Many factors, including hydrology, climate, precipitation, and internal and external processes influenced HW Lake water quality during 1993 and 1994. Studies conducted on two downstream Savannah River system lakes, Richard B. Russell and J. Strom Thurmond, recorded similar patterns of temporal and longitudinal gradients with regard to in situ parameters. While general water quality patterns on HW Lake remained typical for lakes in the region, marked differences occurred between 1993 and 1994.

Minimum recorded temperatures on HW Lake during the study period were approximately 7 °C during February 1994. The onset of thermal stratification occurred in HW Lake during April of 1993 and 1994. By May of each year, extensive stratification existed from the headwaters to the forebay. Stratification was present throughout the study area from HW Dam to the headwaters of the SR embayment from April through October. Maximum temperatures during the months of April through September were observed in the SR embayment headwaters, and surface temperatures reached maxima of 30 °C and 29 °C during August 1993 and July 1994, respectively. Cooling in late September and October of each year decreased surface water temperatures, diminishing vertical thermal gradients. Mixed conditions were observed in the upper SR embayment by October of both years. The HW Dam forebay, where depths exceeded 50 m, remained weakly stratified during November and early December. However, isothermal conditions were observed lakewide by the end of each year.

Maximum DO concentrations (greater than 11 mg/ℓ) were recorded during April 1993 and February and March 1994. Surface DO concentrations averaged 8 mg/ℓ or greater through the year. Hypolimnetic oxygen depletion was observed initially in the upper to midreaches of the SR embayment in April and May of each year. Anoxia in this region was recorded in June and persisted into October. Earlier HW Lake studies included laboratory analyses of nutrient, carbon, and metal concentrations and suggested that mid- to upper SR embayment oxygen depletion was the result of introduction of materials

through inflow loading.[1] Additional studies would be required to accurately determine the cause as point or nonpoint sources.

The anoxic zone, which had originated in the mid- to upper SR embayment, expanded longitudinally and vertically each summer. Progression of anoxia from the midembayment toward HW Dam was observed from July through October. The longitudinal development of downstream anoxia differed during 1993 and 1994 and will be discussed subsequently in relation to hydrology and climate. Stratification and accompanying anoxia in the upstream regions were diminished by early October due to seasonal cooling and mixing processes. By November, anoxic conditions were observed only in areas of HW Lake greater than 30 m in depth. From late December through February, DO concentrations lakewide were at or near saturation.

Seasonal trends in specific conductance on HW Lake were similar to those observed for DO concentration during 1993 and 1994. Specific conductance values throughout the summary period increased coincident with the formation and expansion of hypolimnetic anoxia. Conductivity values greater than 100 μS were observed in the mid-SR embayment during early to midsummer. During May through July 1993, conductivity increased to greater than 200 μS. Specific conductance maxima of 300 μS were recorded in September. By October, seasonal cooling and reaeration, combined with oxygenated inflows, had displaced anoxia in the upper SR embayment, and increased conductivity values were recorded in a plume-like layer at depths of 20 to 30 m at midlake stations, coincident with the approximate penstock withdrawal depths at HW Dam. October was the last month of 1993 that conductivity values greater than 100 μS were observed. The HW Lake forebay station exhibited maximum conductivity of 80 μS in November. Lakewide mixing was complete by late December 1993, and conductivity averaged 30 μS. Specific conductance patterns in 1994 were dissimilar. While conductivity values greater than 100 μS were recorded in bottom waters in the upper SR embayment during the majority of the stratified period, recorded maxima did not exceed 200 μS during 1994. These differences may be directly attributed to hydrological and climatological conditions and will be discussed subsequently.

At the forebay station, thermocline depth during the May through October stratified period ranged from 6 to 22 m. The gradual deepening of the thermocline can be attributed to hypolimnetic penstock withdrawals, seasonal warming, and inflows. Temperatures during stratification in the epilimnion ranged from 22 to near 30 °C. While slightly higher surface temperatures were recorded in 1993, increased warming of the epilimnion was evident during 1994. Heavy inflow and discharge rates during summer 1994 resulted in an

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[1] Jabour, W. E., and Carroll, J. H. (1993). "Water quality studies: Hartwell Lake 1991 summary report," Miscellaneous Paper EL-93-20, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Huffstettler, C. J., and Jabour, W. E. (1993). "Water quality studies: Hartwell Lake 1992 summary report," Miscellaneous Paper EL-93-21, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

overall warming of 2 to 5 °C over 1993 from the surface to bottom. Anoxia in forebay bottom waters was first observed in mid-September of each year. During 1994, a metalimnetic minimum of 1.5 mg/ℓ at 18 to 20 m was recorded. DO concentrations were 5.5 mg/ℓ directly above and 3.2 mg/ℓ directly below this layer. This phenomenon, directly related to hydrology, was not observed during 1993. Forebay anoxia, although diminished, persisted during November and early December at depths greater than 50 m. Specific conductance, while averaging 30 μS surface to bottom during January through August, reflected the downstream progression of lesser DO water during late summer and autumn of both 1993 and 1994. Maximum concentrations of approximately 65 μS and 100 μS were recorded at the bottom depths during November 1993 and December 1994, respectively.

As a water management strategy, HW Lake is regularly drawn down during the late summer and fall in preparation for winter and early spring rainfall. Precipitation during 1993 was maximal during winter and spring, and minimal during midsummer. This trend was reversed in 1994, when greatest precipitation was recorded during midsummer. Total inflow during August 1994, when precipitation exceeded 26 cm, was nearly five times greater than during August 1993. Consequently, while discharge through HW Dam in August 1993 averaged approximately 100 m^3s^{-1}, the 1994 average increased to 270 m^3s^{-1}. These increases were due in great part to precipitation associated with a midmonth tropical storm, the inflow from which necessitated a combination of tainter spills and 24-hr generation totaling approximately 2,000 m^3s^{-1} during 17-18 August. This resulted in greater in-lake flows, a lower residence time for water moving from the SR embayment, and significant change in thermocline depth at HW Dam.

Figure 28 depicts DO concentrations during the midsummer months of 1993 and 1994. Evidence of this increased interflow is exhibited in the plume layer of decreased DO concentration observed in the upper to midembayment. The variability in the shape of the plume has a direct relationship to HW Lake inflow volume and HW Dam discharge. During summer 1994, increased inflows and hypolimnetic releases through the HW Dam resulted in a finger-like projection of decreased DO concentration between 20 and 30 m, coincident with the penstock withdrawal zones. Progression of anoxia, both spatial and temporal, resulted in a 1.5-mg/ℓ DO minimum at depths of 18 to 20 m during September at the forebay station. DO concentrations greater than 3 mg/ℓ were recorded above and below the plume. During 1993, a year in which the interflow was reduced or absent, the downstream progression of anoxia remained confined to HW Lake bottom waters, with no evidence of middepth minima. However, conditions were improved in 1994 since the oxycline occurred at greater depths and the volume of anoxic water was reduced.

Specific conductance during 1994 was also directly impacted by climatological and hydrological events (Figure 29). Lakewide conductivity maxima during July, August, and September 1993 were recorded in the midreaches to upper reaches of the SR embayment. Increased upstream inflows and

HW Dam releases during midsummer 1994 resulted in a downstream progression or flushing of increased conductivity values to midlake stations greater than 40 m in depth approximately 2 months earlier than was observed in 1993. Without this pronounced interflow during 1993, this downlake progression was not completed until November.

In conclusion, water quality conditions at HW Lake during 1993 and 1994 were influenced by many factors, including hydrodynamics, climatological conditions, seasonal variability, anoxic development and duration, loading, and additional internal and external limnological processes. The farthest uplake stations in SR embayment exhibited greatest variability in water quality in terms of DO concentration and increased conductivity values throughout the early summer to midsummer period. Forebay, and subsequently release, water quality was directly influenced during August and September by water quality conditions in the upstream reaches. Notable differences in DO and specific conductance gradients during 1993 and 1994 were the direct result of increased precipitation, inflow, and subsequent discharge.

6 Recommendations

The following are recommendations regarding future HW Lake water quality investigations:

a. Studies conducted on HW Lake in 1993, consisting of nine in situ sampling trips, form the basis for the minimum effort necessary to adequately define ongoing water quality trends and patterns. Although long-term analyses are possible with this level of monitoring, such a database offers limited utility for the assessment of likely questions such as those related to future loading, land-use related watershed impacts, and the effects of riparian development. For these reasons, it is recommended that future work continue at this present effort or increase in scope.

b. The present sampling sites in the main embayment of HW Lake and SR embayment were selected based on cost considerations and earlier issues related to the SR embayment. Consideration should now be given to expanding ongoing studies to include the Tugaloo River embayment.

c. Surveys of HW Lake presently include only those limnological characteristics that can be measured using in situ instrumentation. Important facts about HW Lake are not known as a result of such surveys because they do not include laboratory analyses of critical chemical constituent nutrients (e.g., organic material). Laboratory analyses should be reinstated on a bi-monthly basis.

d. Preparation of a hydrodynamic model would contribute to existing knowledge of in-lake processes influencing material transport. Emphasis should be on embayments and their likely impact on the lake hydrodynamics. Such a model would be a prerequisite for any future water quality modeling efforts.

e. In preparation for or in conjunction with the development of a modeling study, the observed trends in the SR embayment should be explored in detail to identify the nature and source of the oxygen-consuming materials that may impact the downstream reaches of HW Lake. The goal of such a study would be to find a solution to existing

problems with release water quality and with detrimental entrainment of fish through the turbines. A study of loading to the embayment as well as a study of in-lake chemical and biological processes is recommended.

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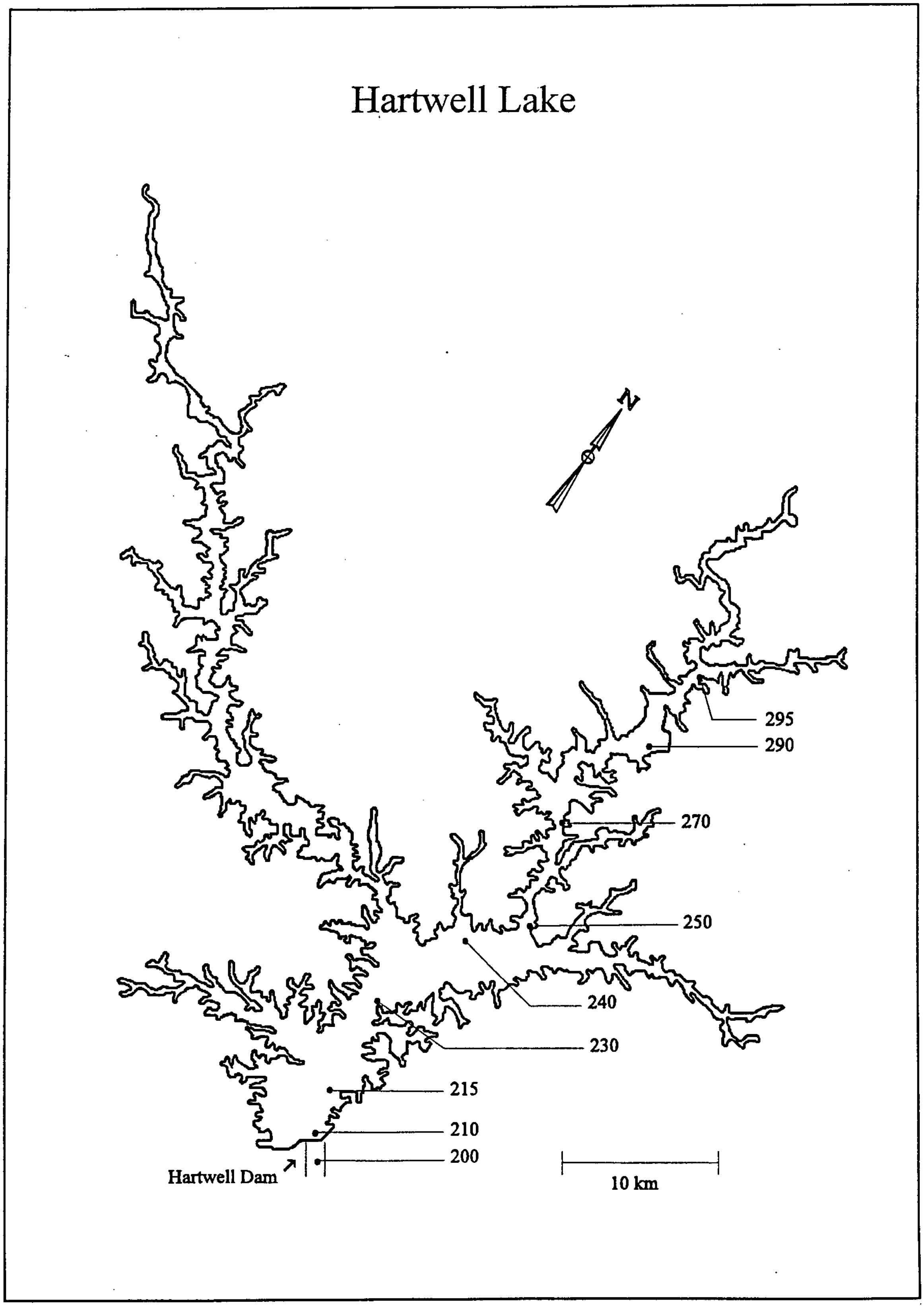


Figure 1. Sampling stations on Hartwell Lake

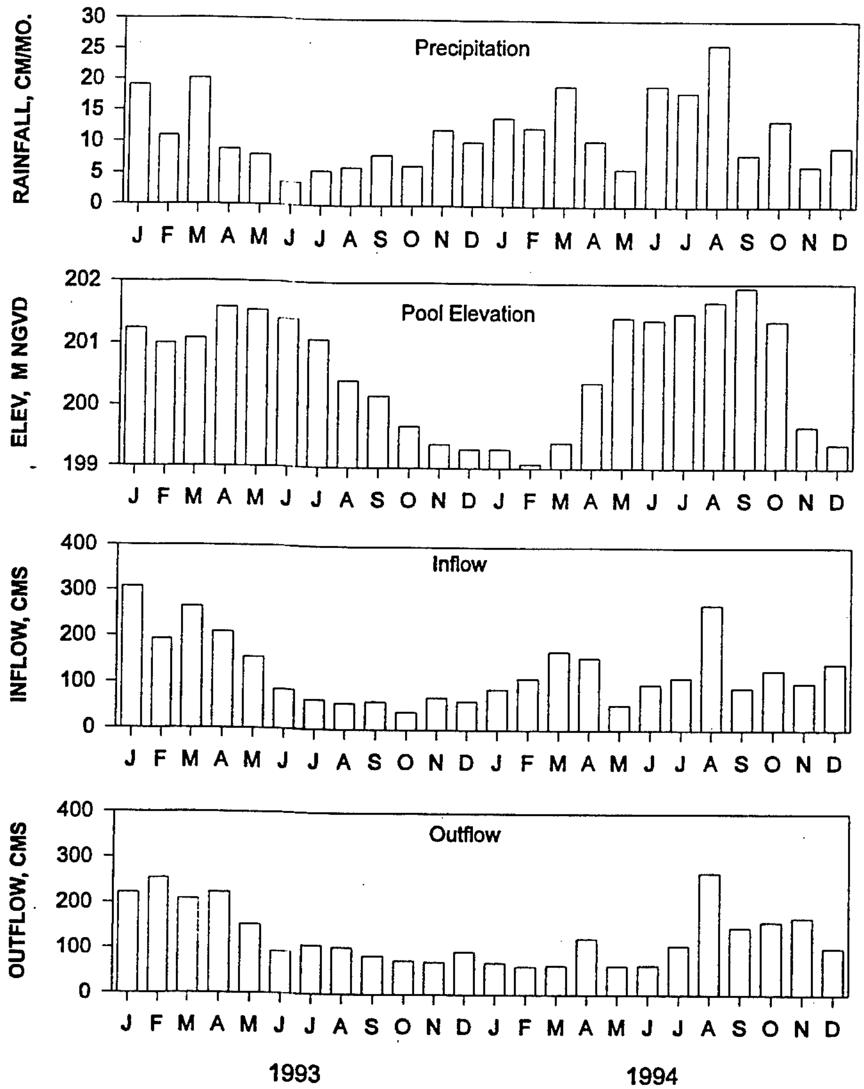


Figure 2. Hartwell Lake precipitation, pool elevation, and mean daily inflow and outflow for 1993 and 1994

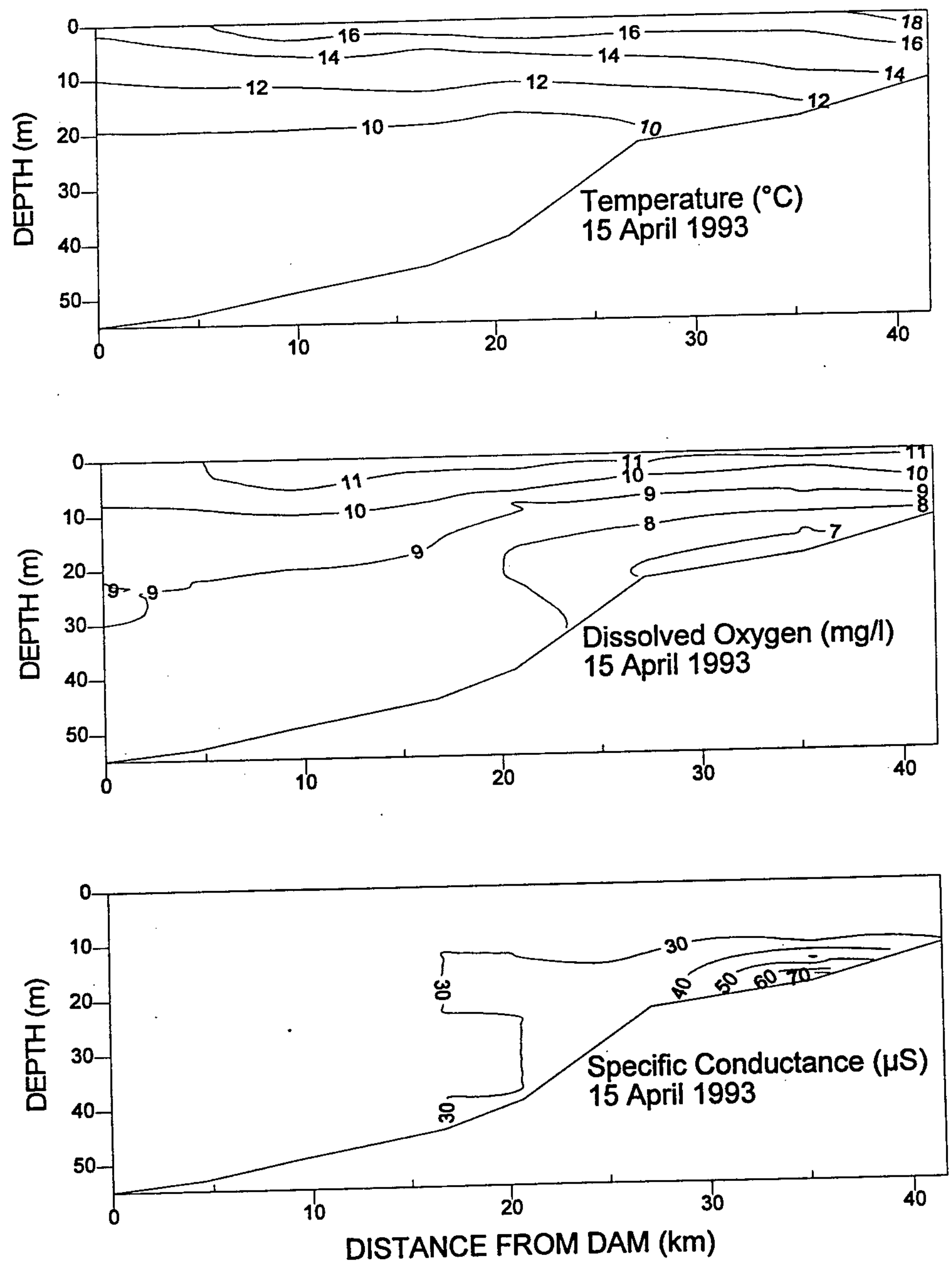


Figure 3. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (μS) from Hartwell Dam to upper Seneca River embayment for 15 April 1993

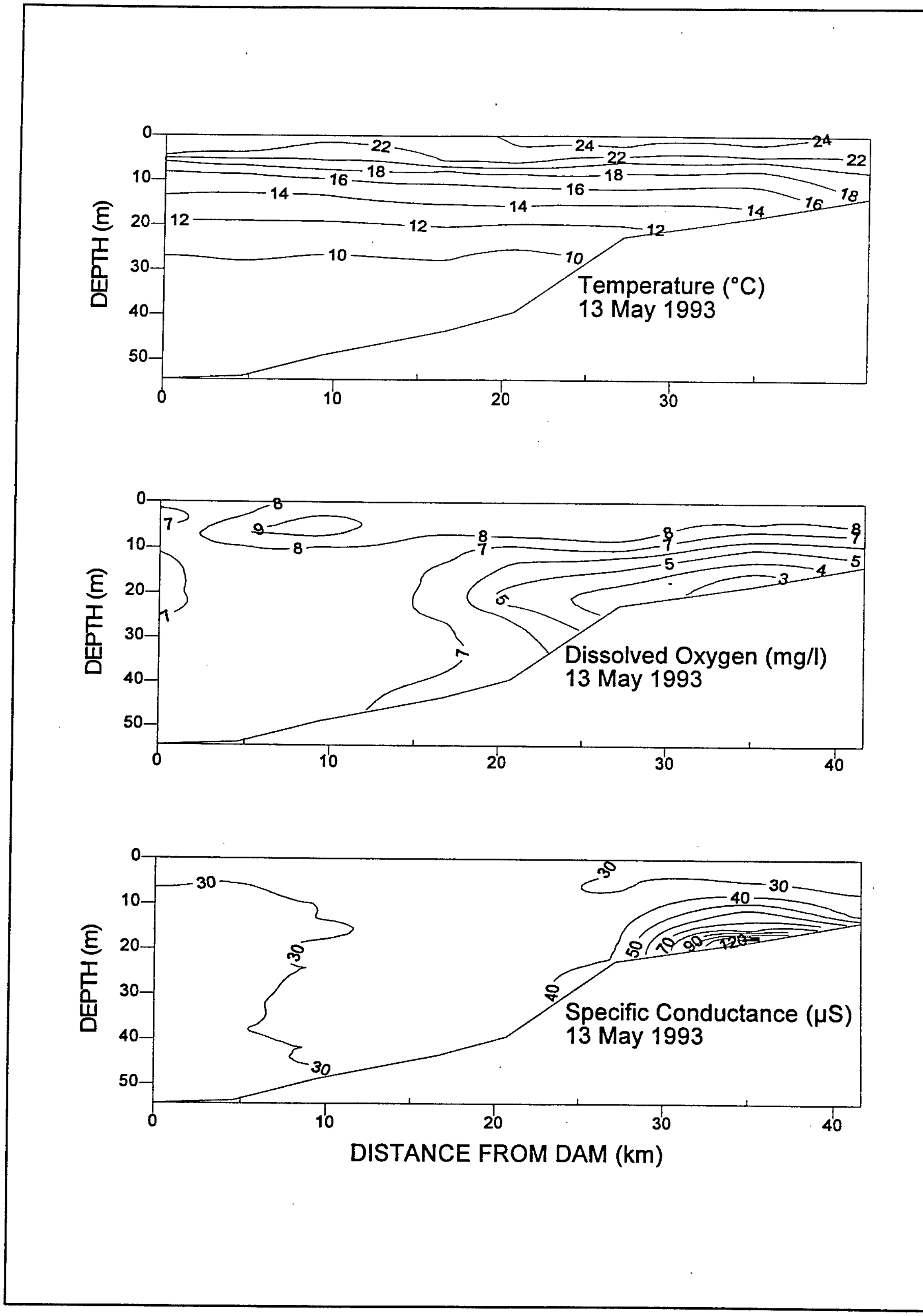


Figure 4. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 13 May 1993

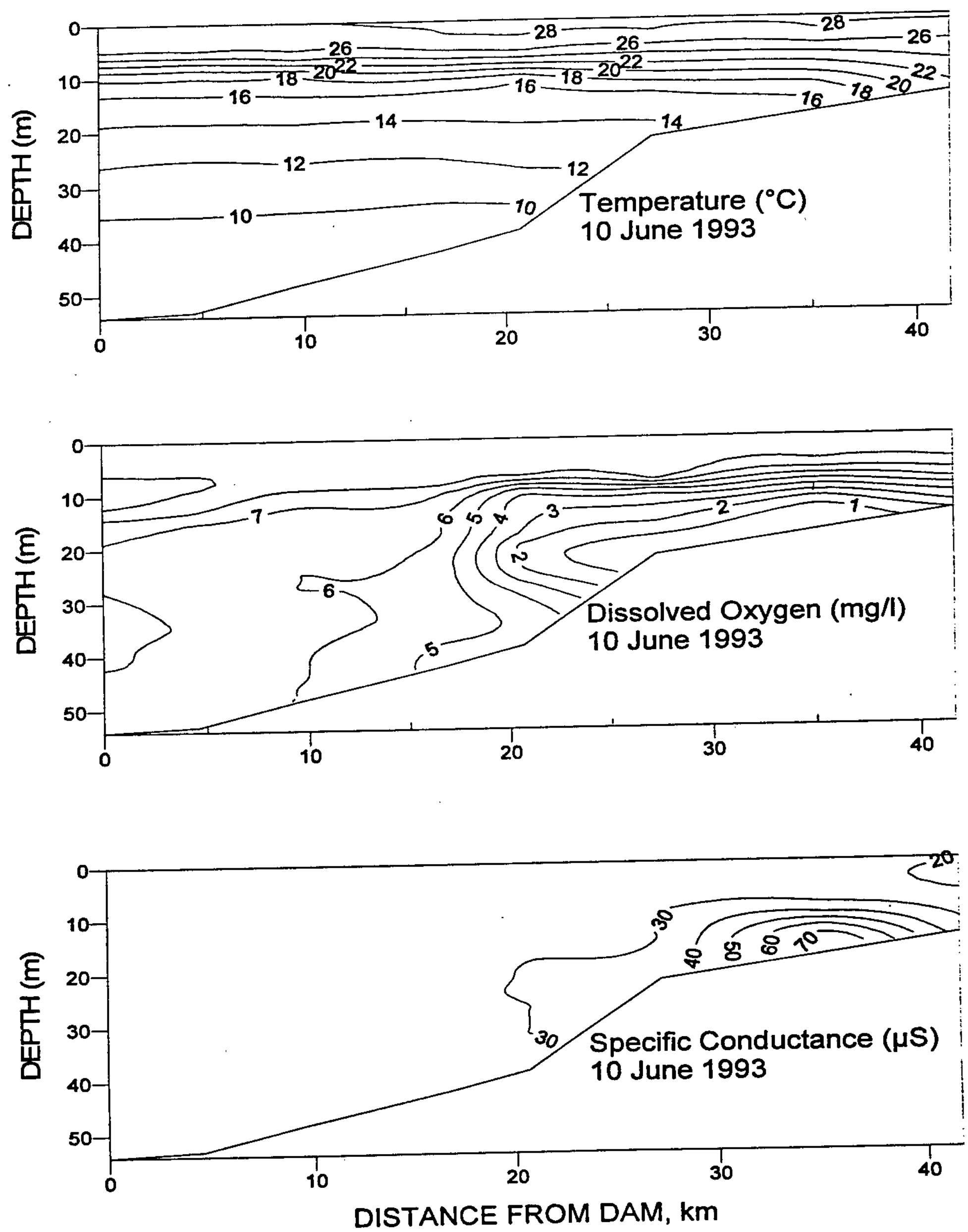


Figure 5. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 10 June 1993

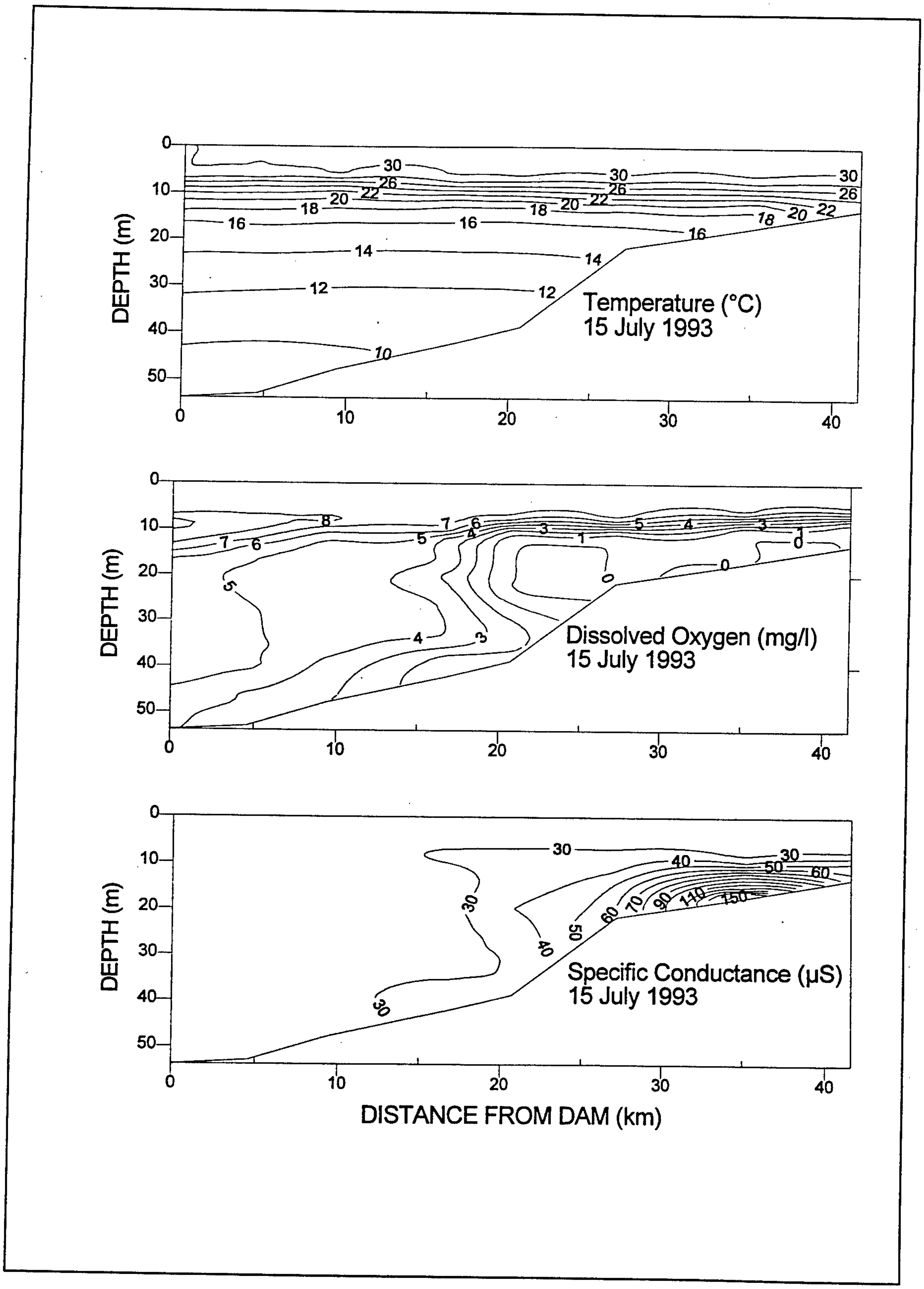


Figure 6. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 15 July 1993

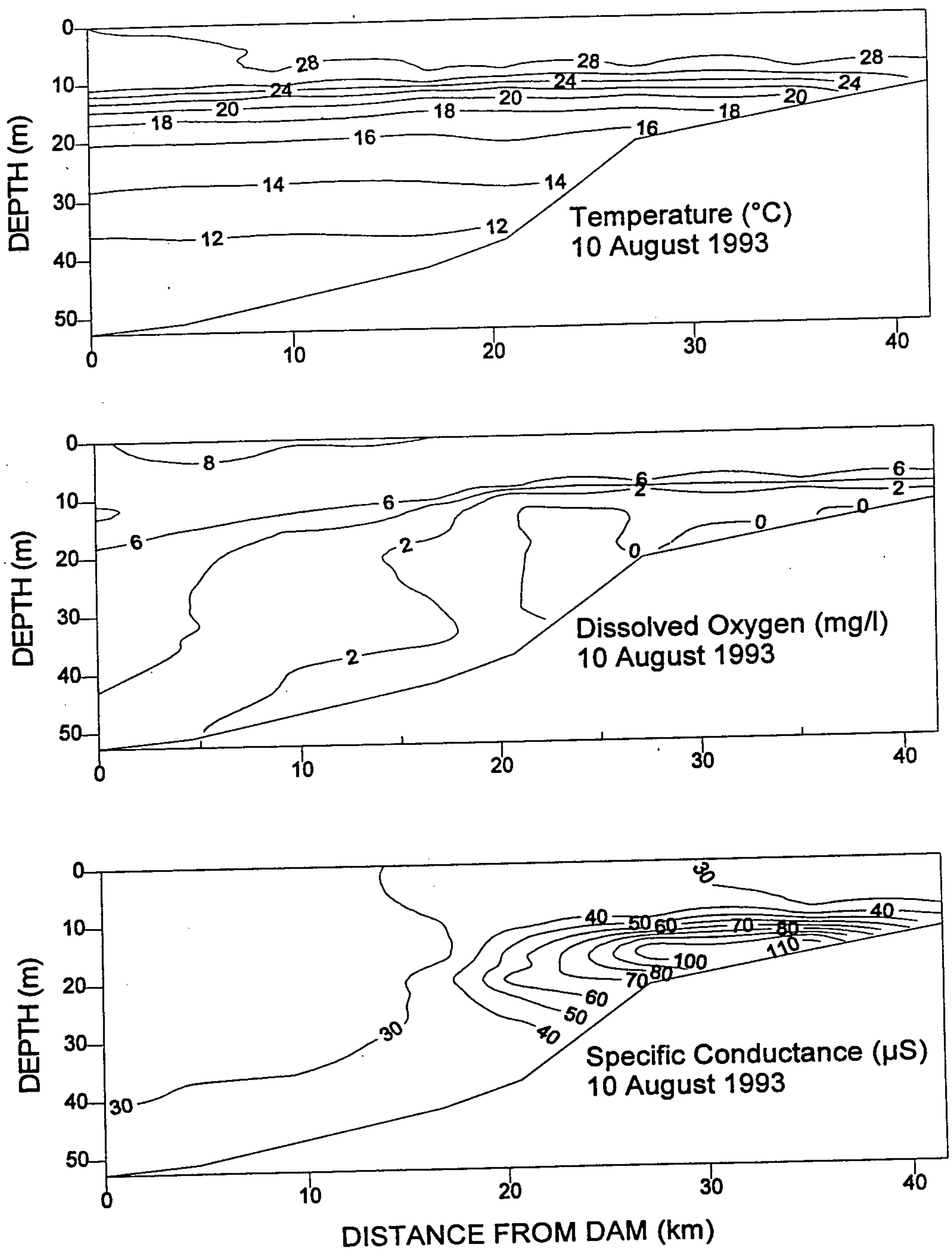


Figure 7. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 10 August 1993

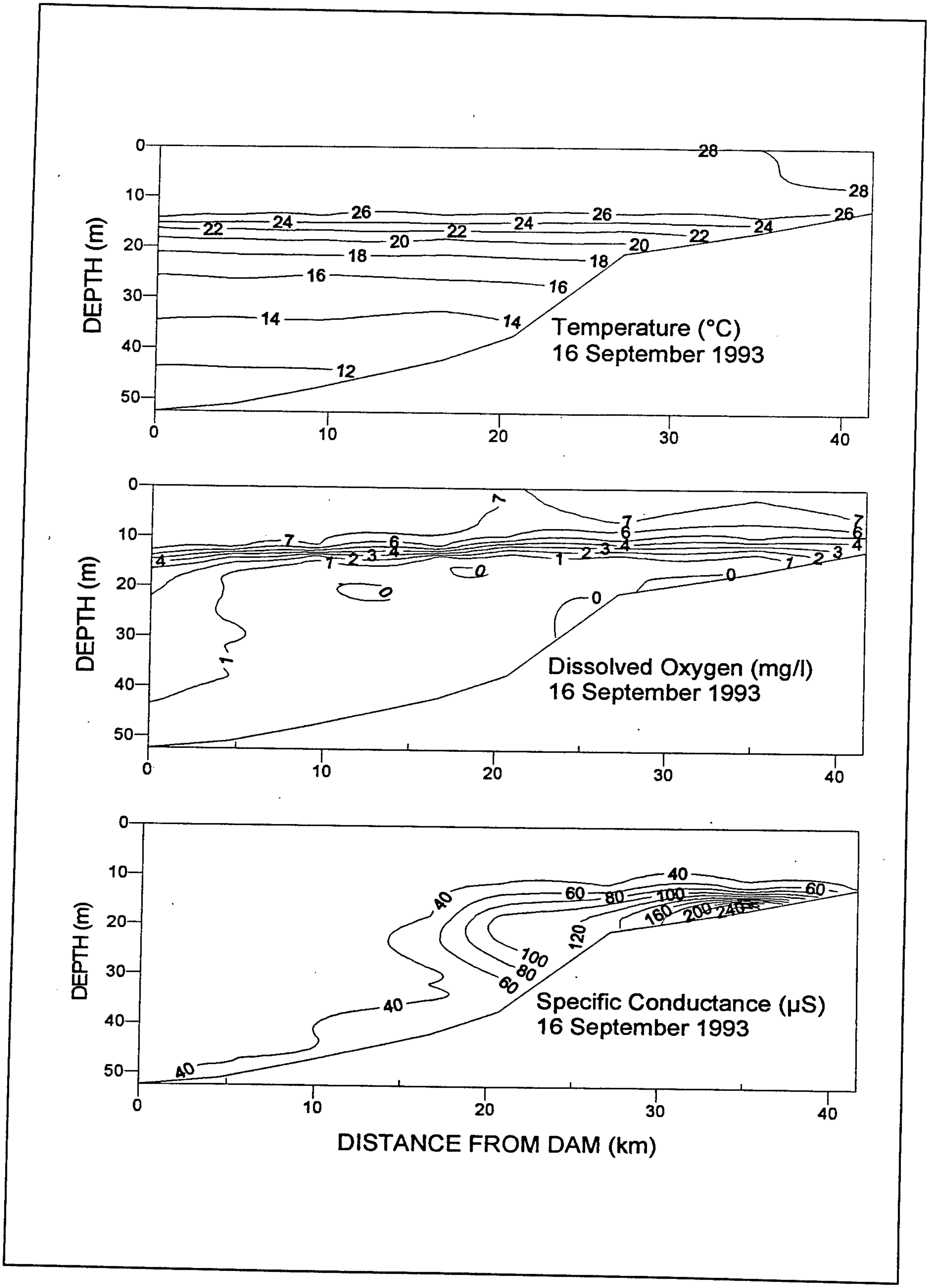


Figure 8. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 16 September 1993

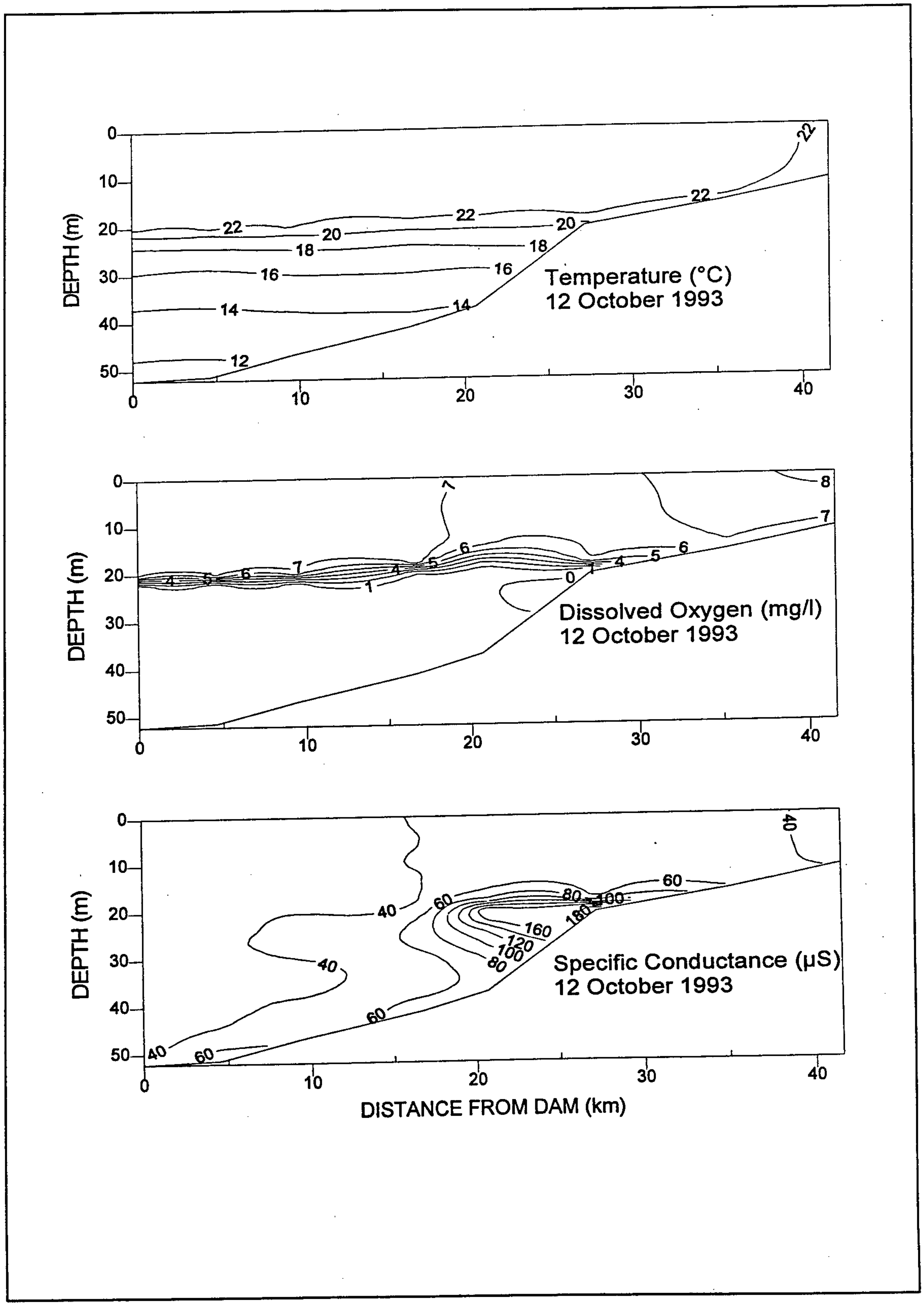


Figure 9. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 12 October 1993

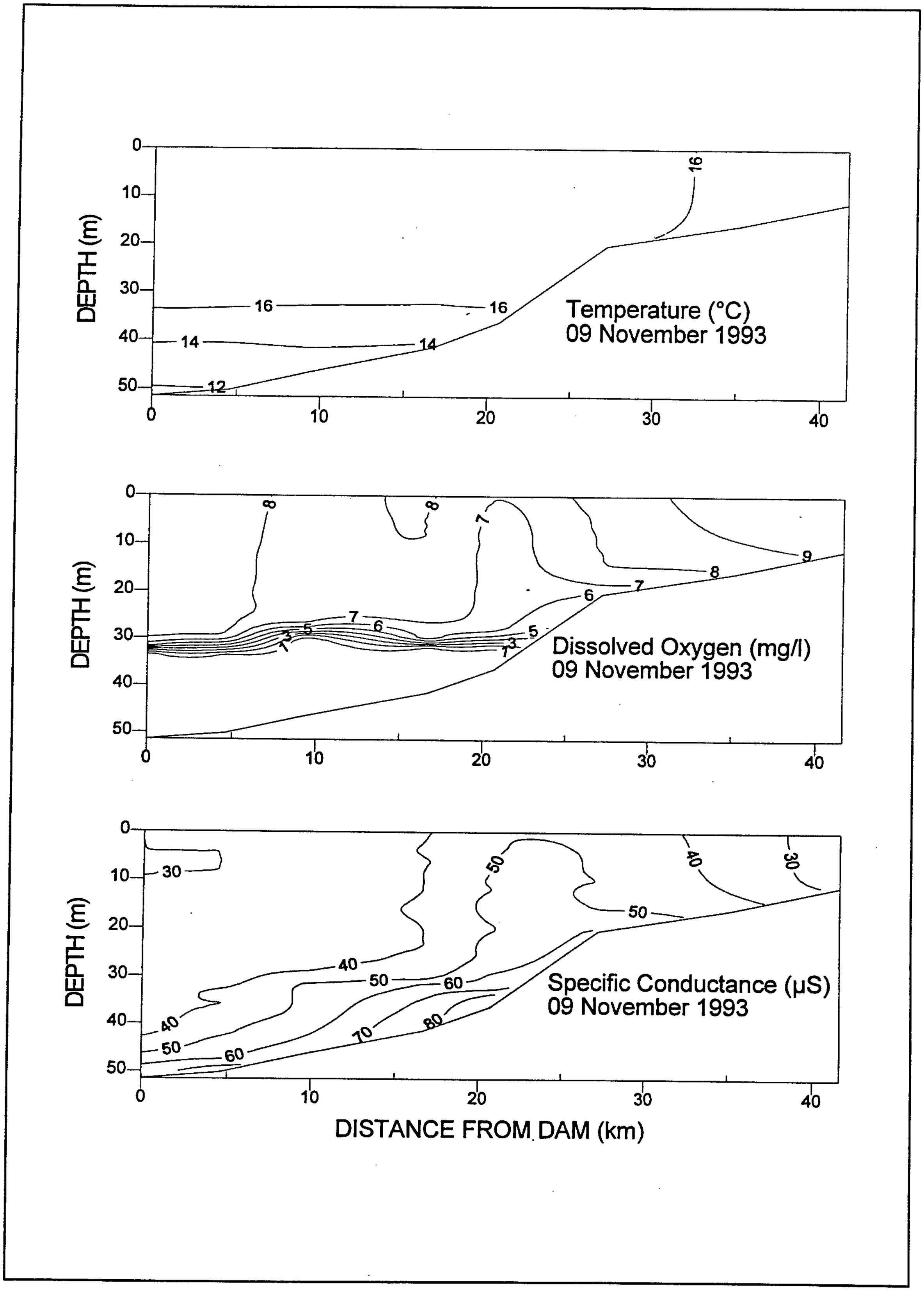


Figure 10. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 09 November 1993

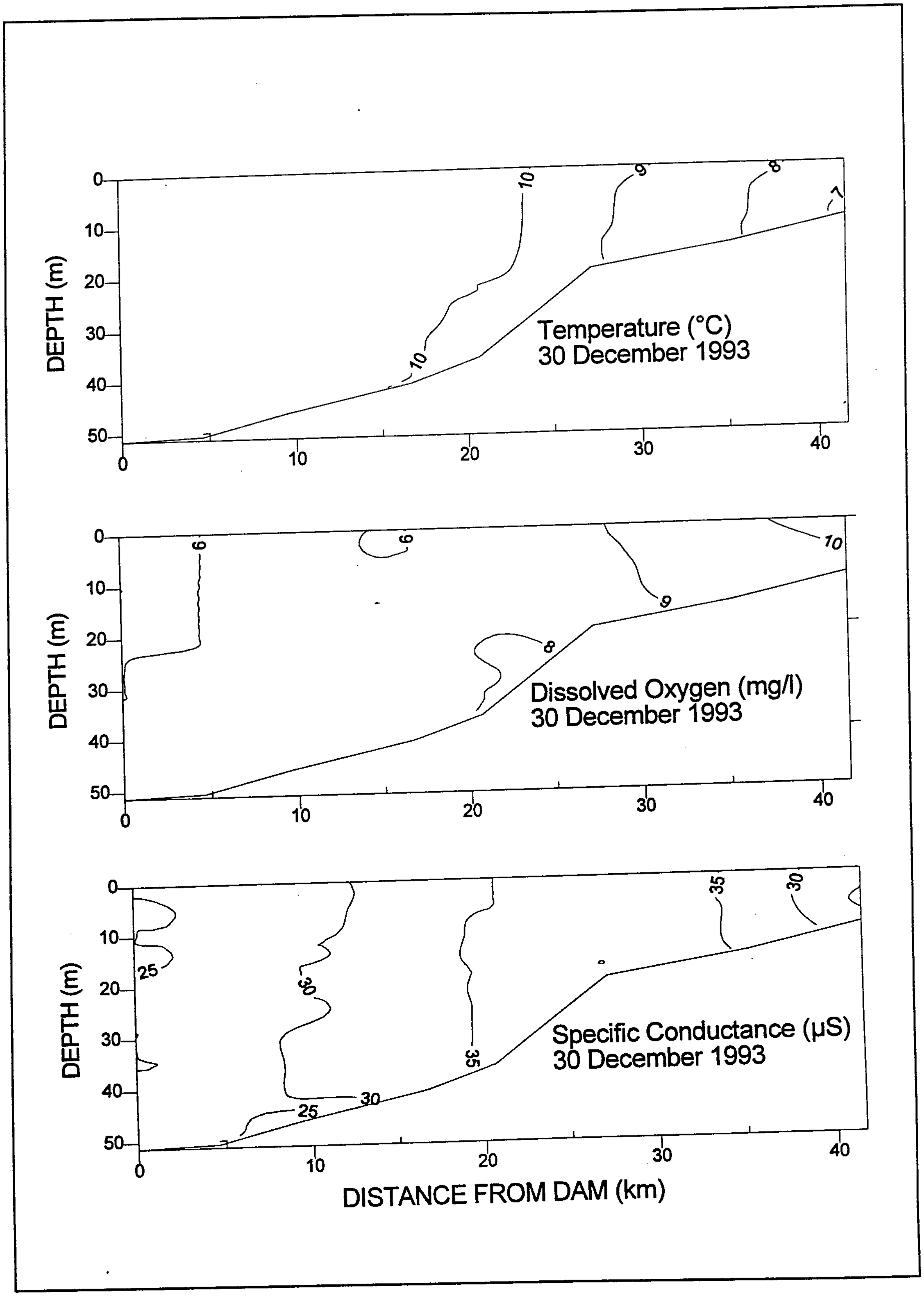


Figure 11. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (μS) from Hartwell Dam to upper Seneca River embayment for 30 December 1993

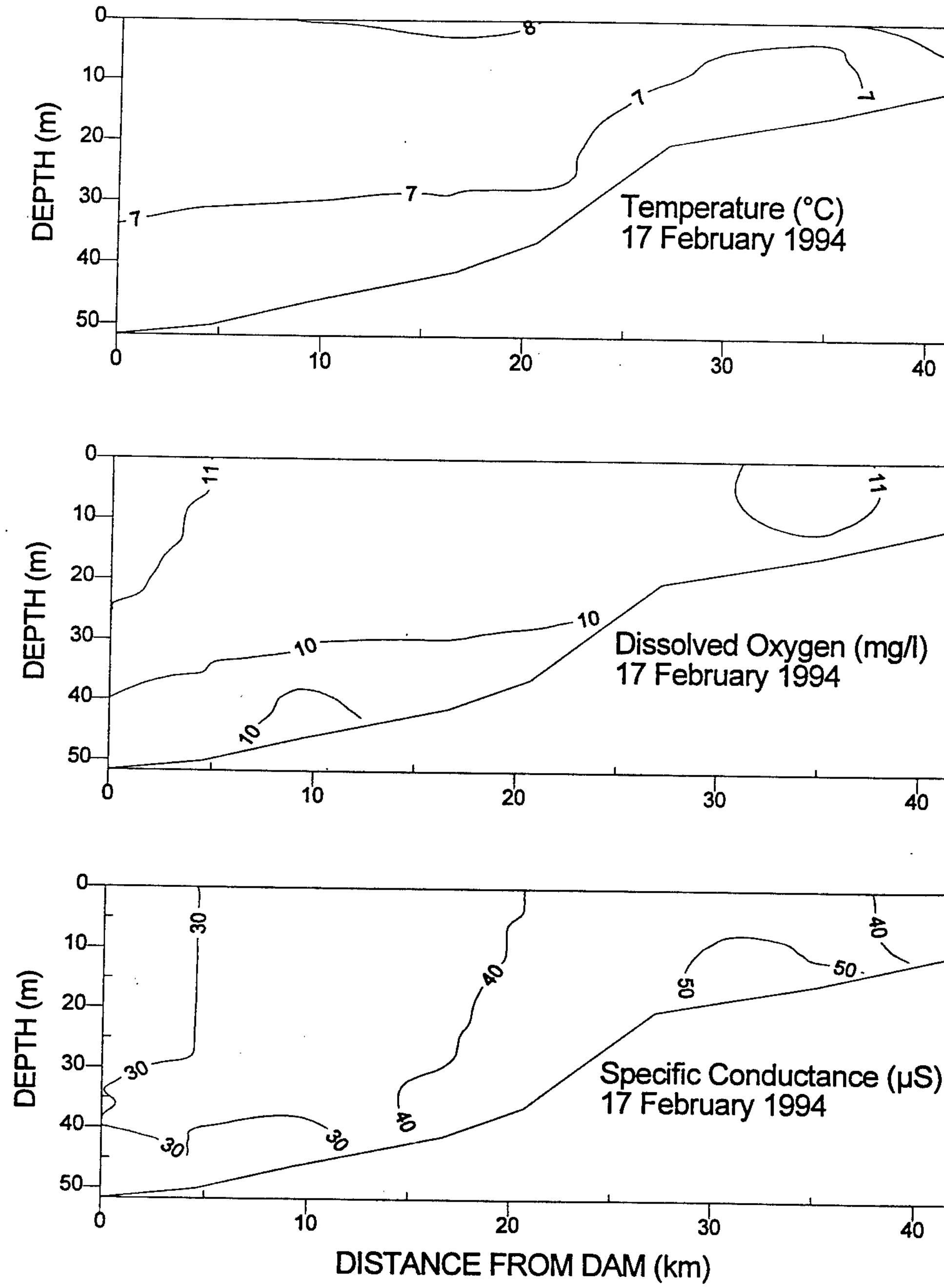


Figure 12. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 17 February 1994

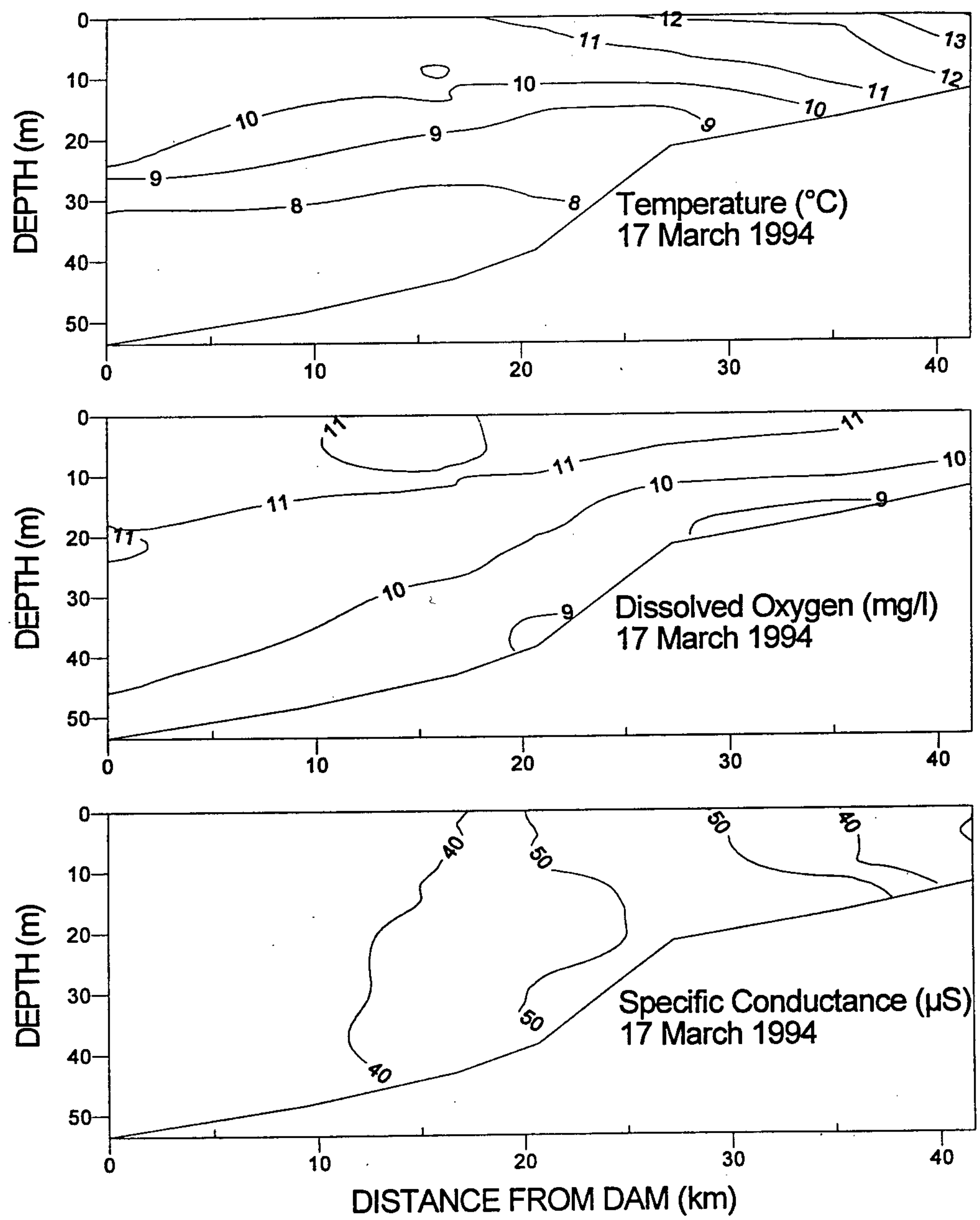


Figure 13. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 17 March 1994

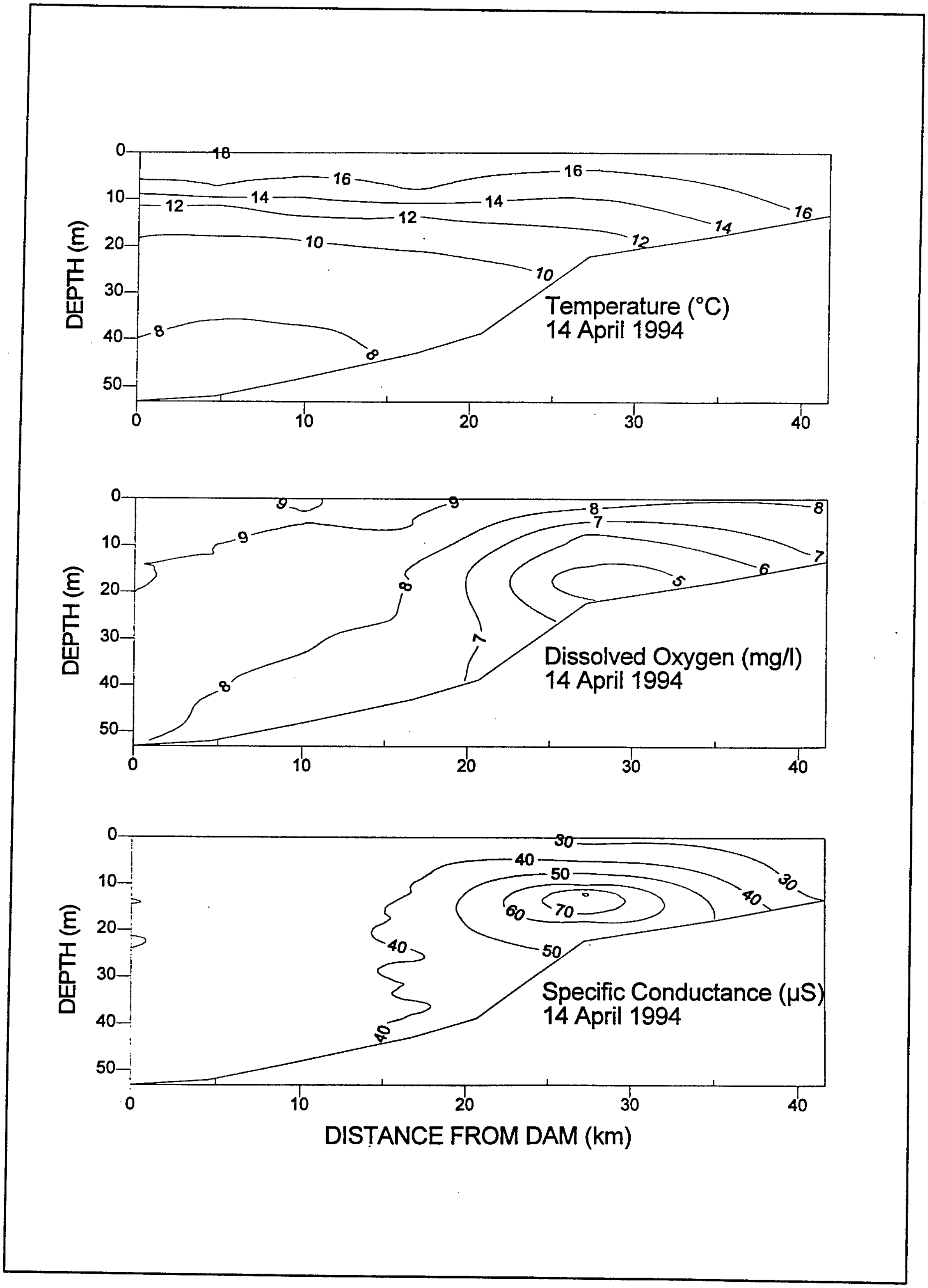


Figure 14. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 14 April 1994

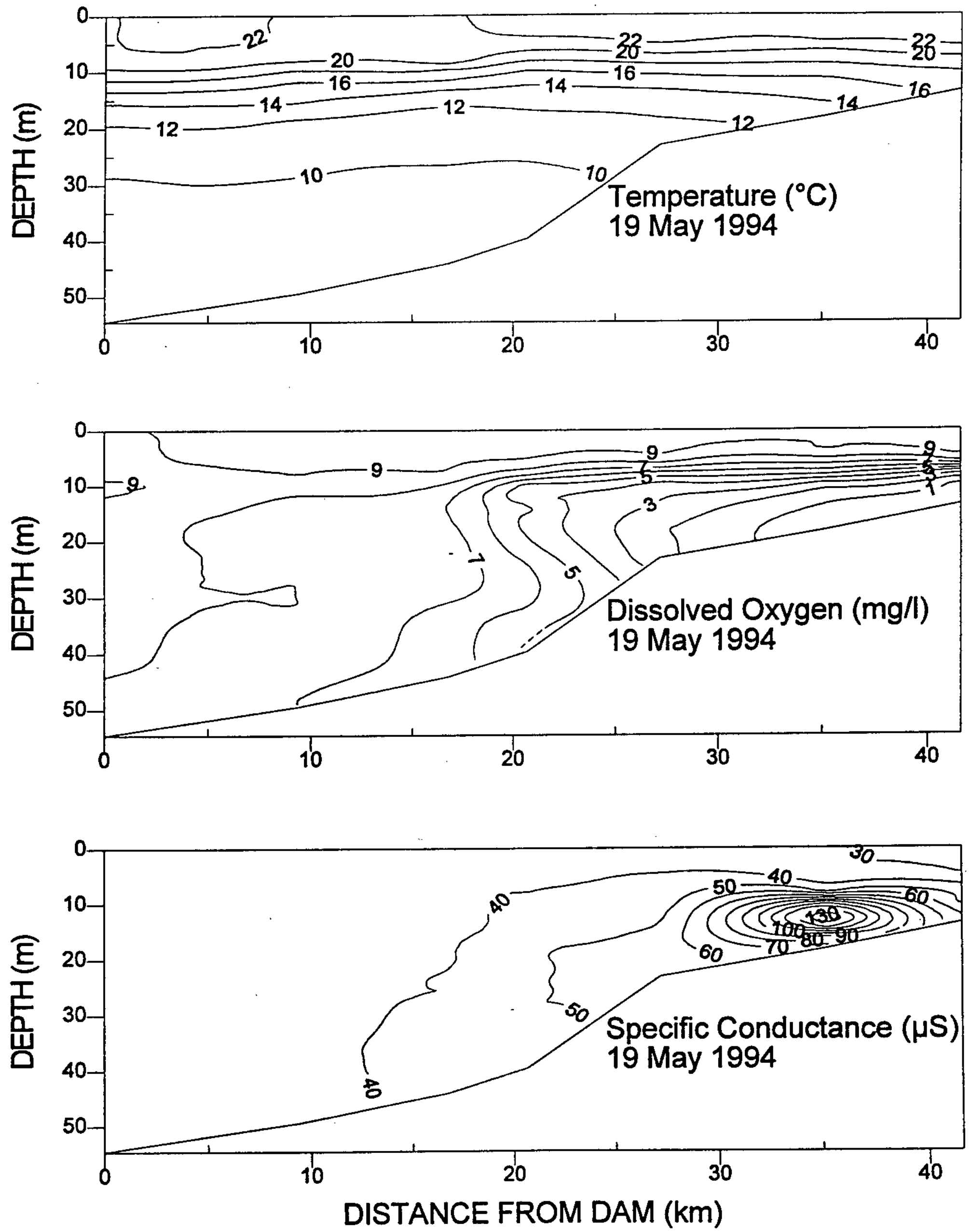


Figure 15. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (μS) from Hartwell Dam to upper Seneca River embayment for 19 May 1994

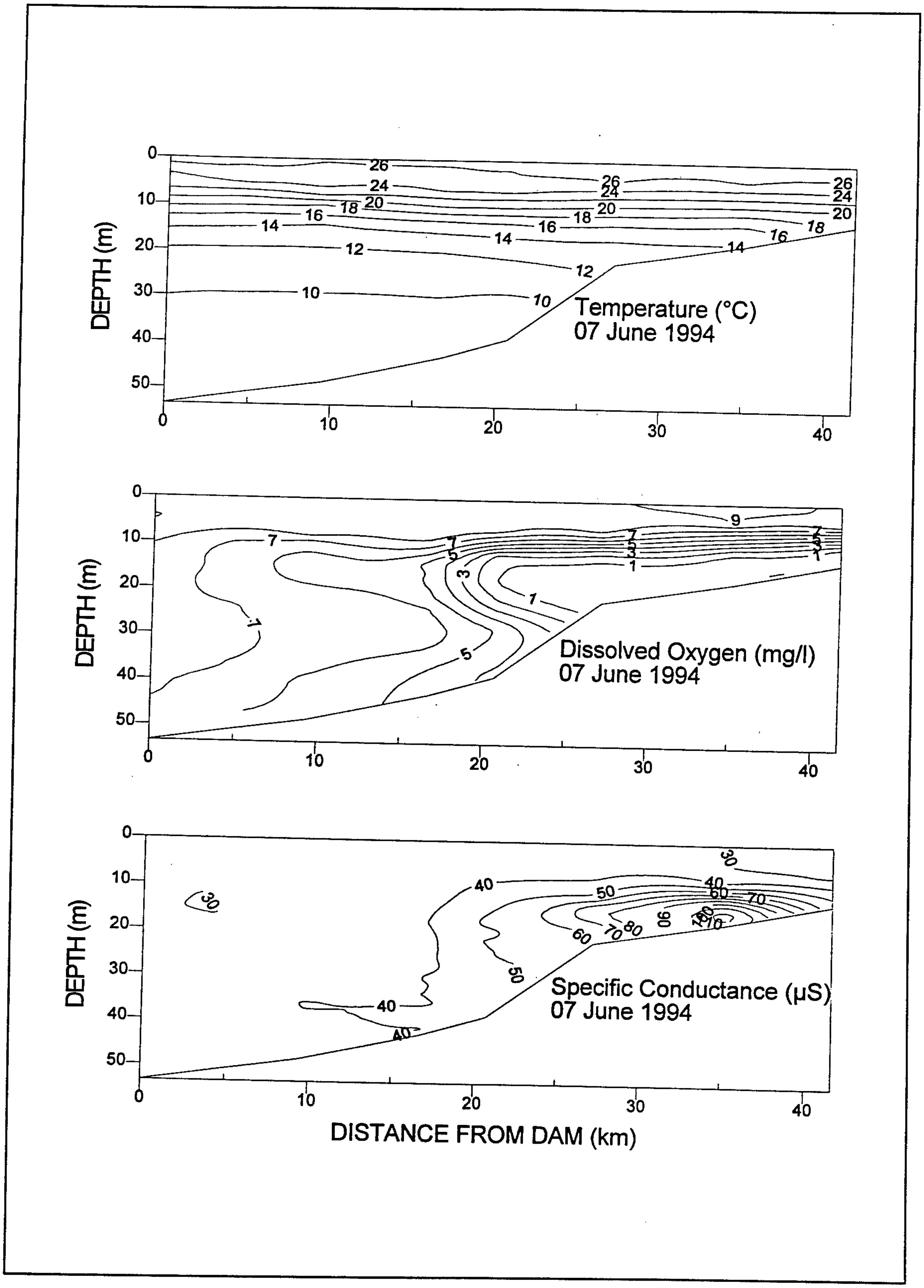


Figure 16. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 07 June 1994

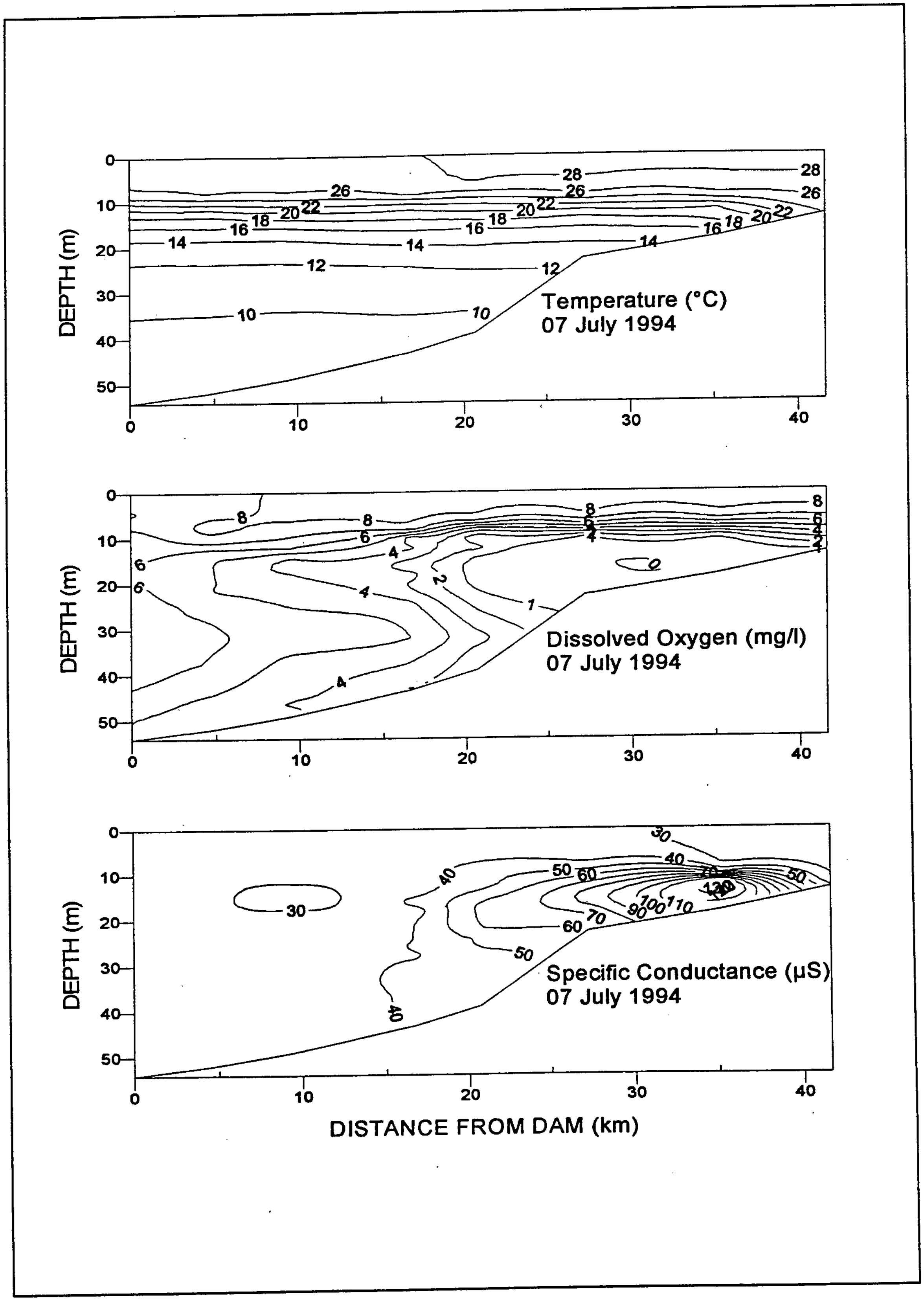


Figure 17. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 07 July 1994

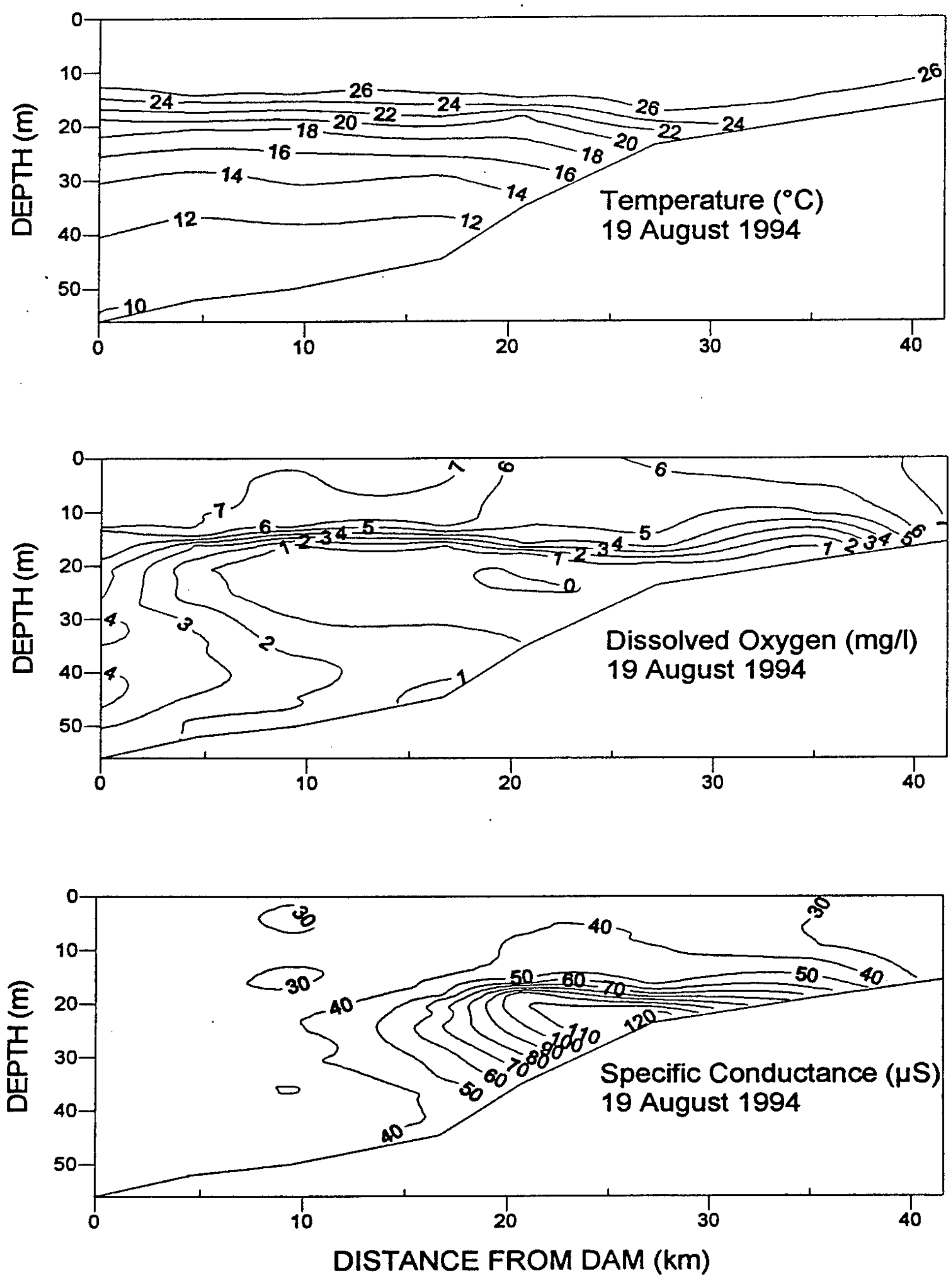


Figure 18. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (μS) from Hartwell Dam to upper Seneca River embayment for 19 August 1994

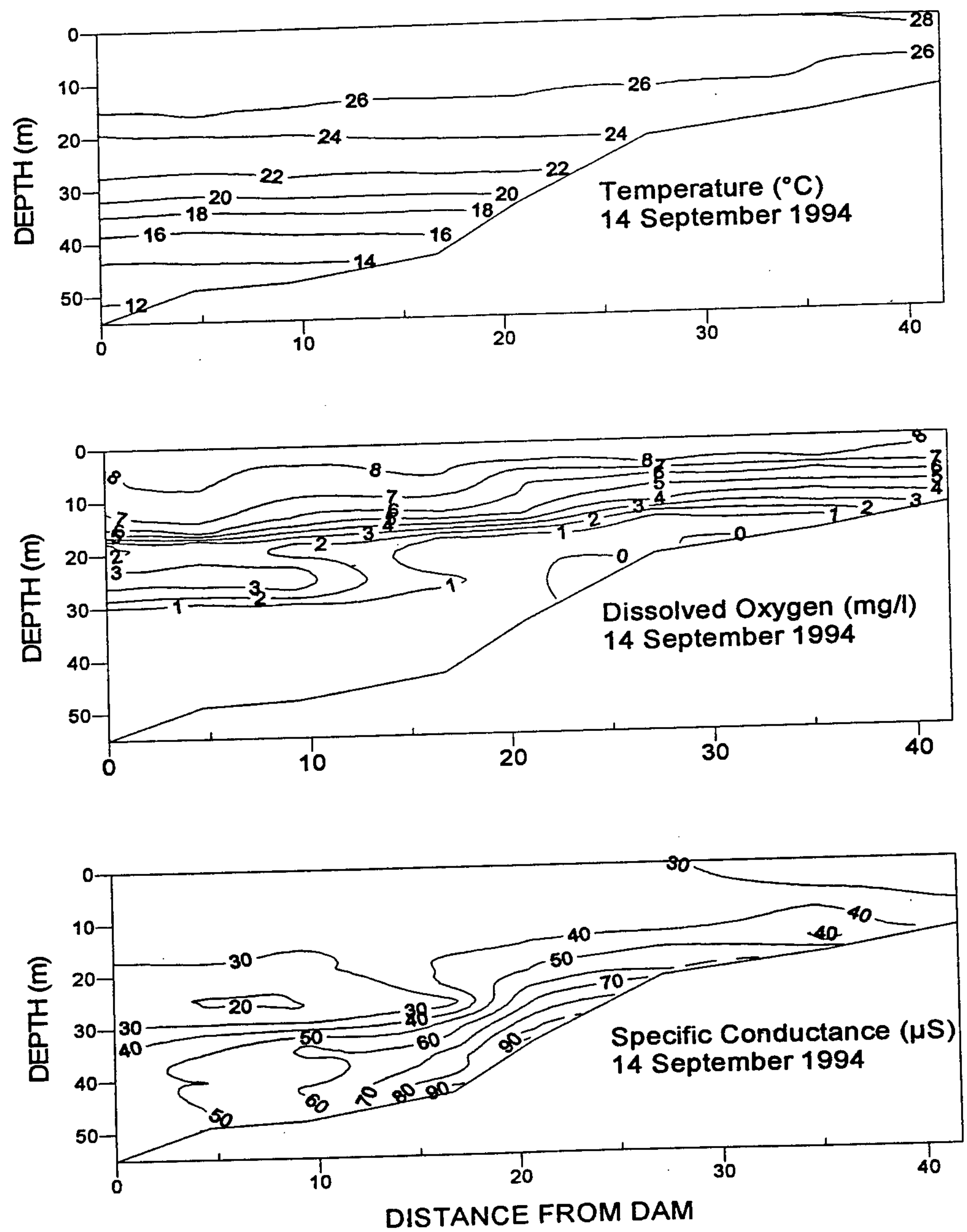


Figure 19. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 14 September 1994

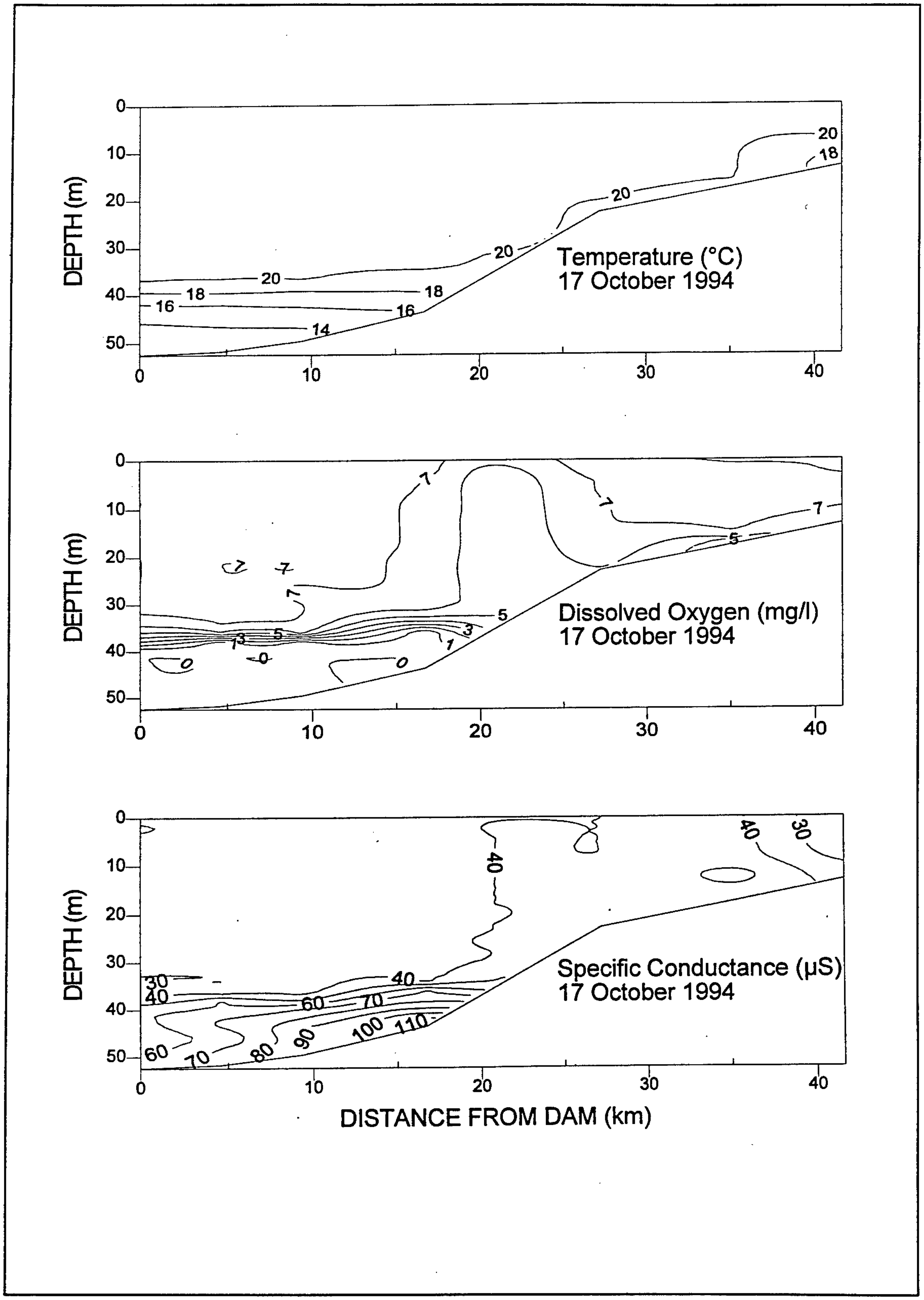


Figure 20. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (μS) from Hartwell Dam to upper Seneca River embayment for 17 October 1994

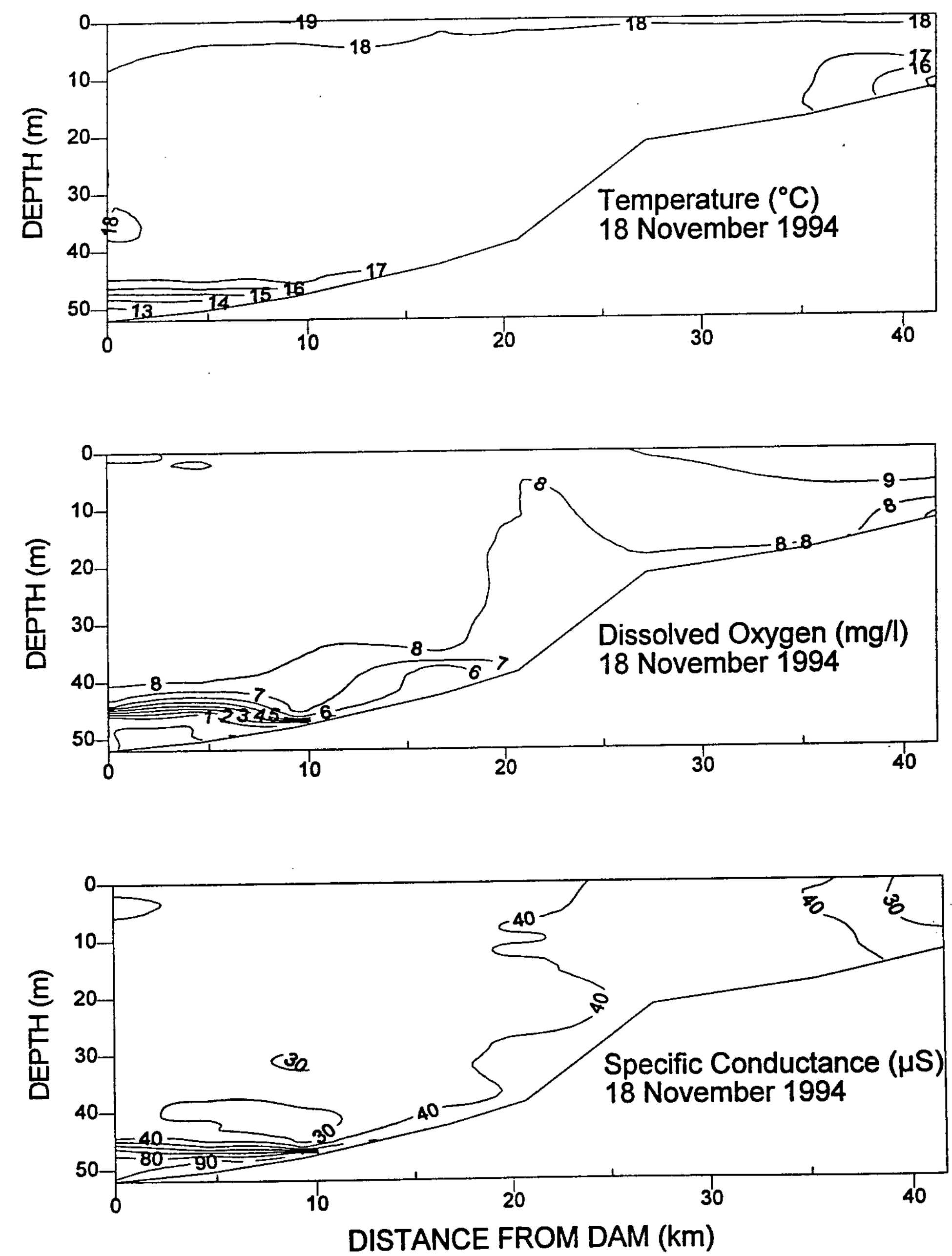


Figure 21. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 18 November 1994

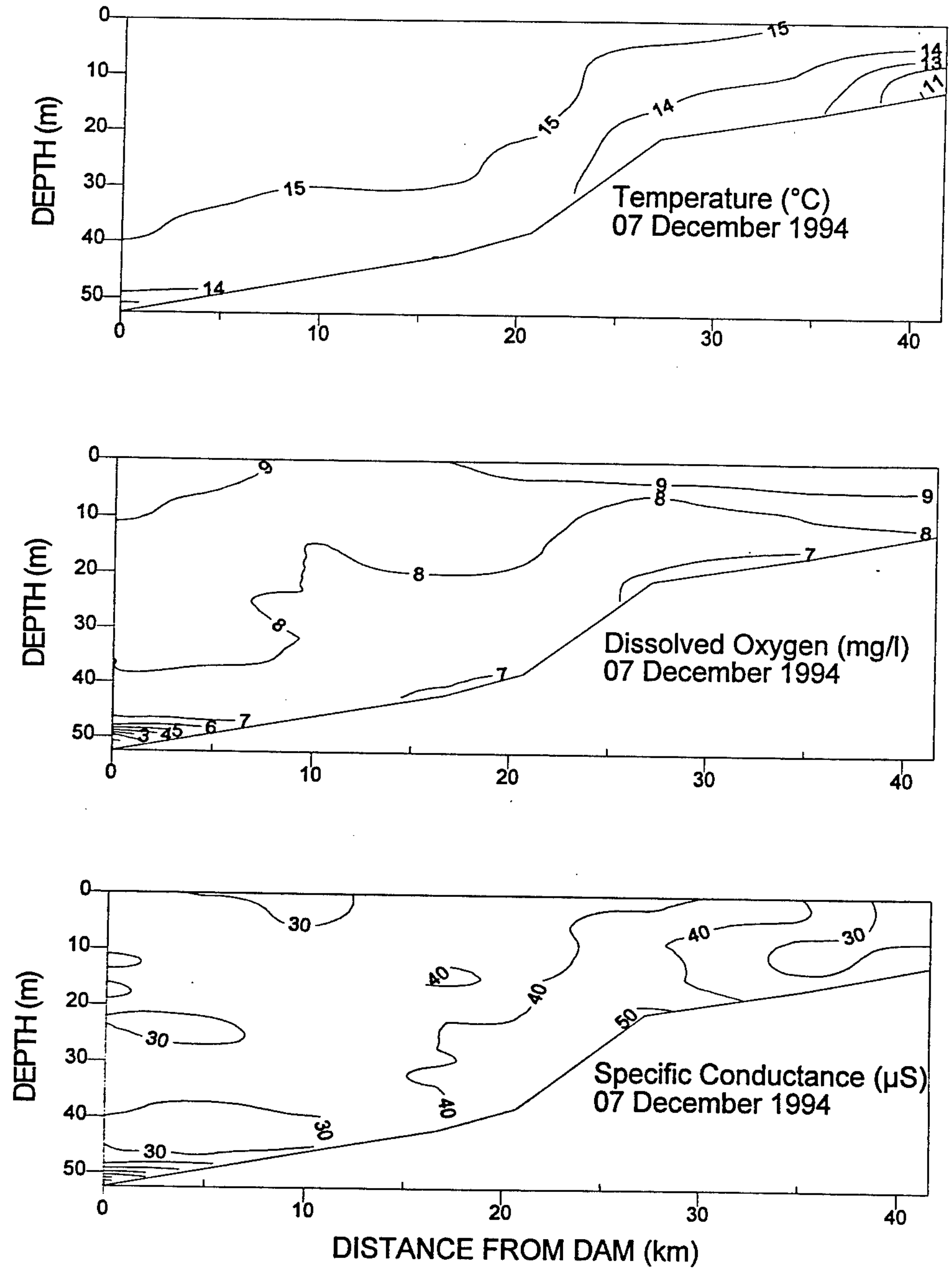


Figure 22. Spatial distribution of temperature (°C), dissolved oxygen (mg/ℓ), and specific conductance (µS) from Hartwell Dam to upper Seneca River embayment for 07 December 1994

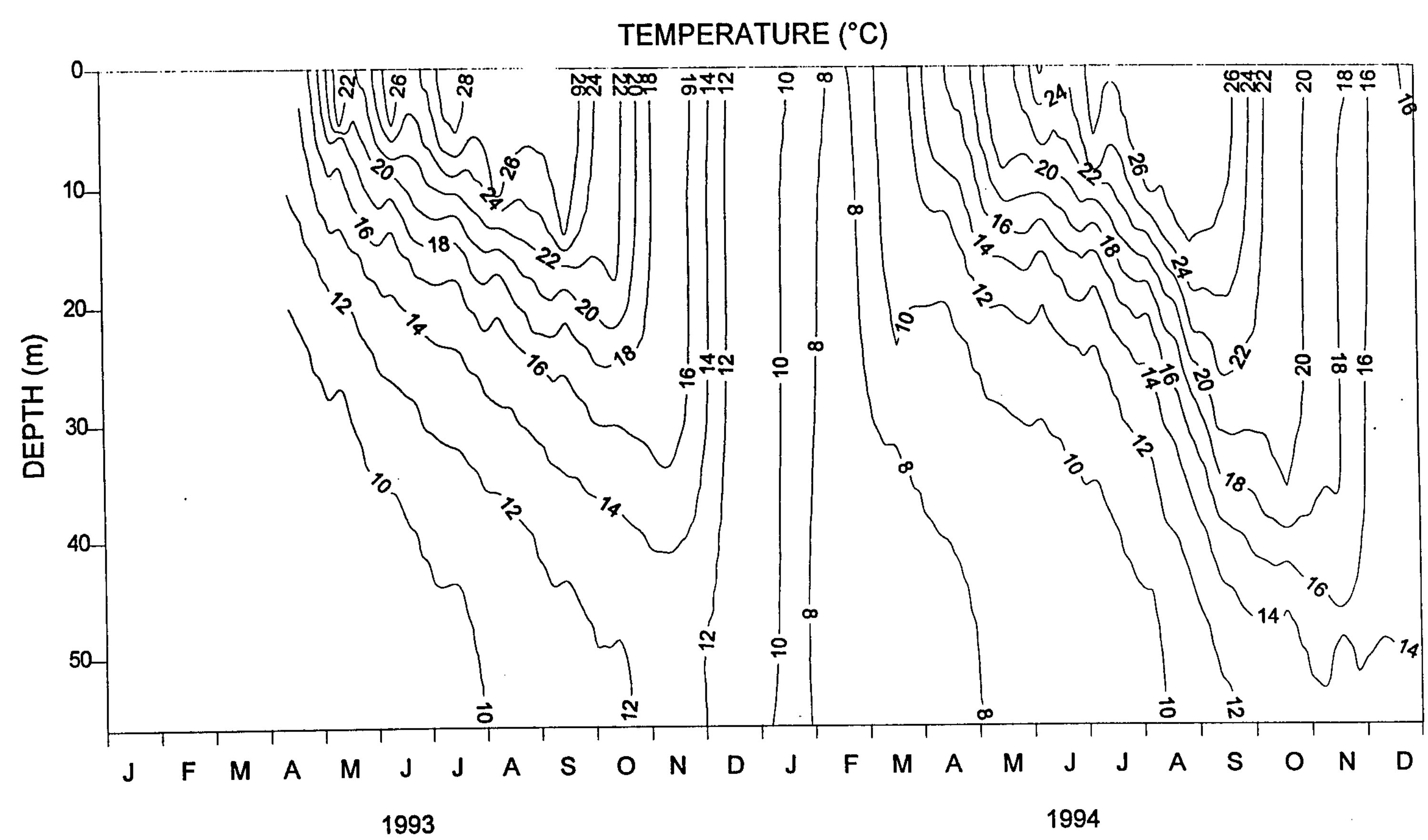


Figure 23. Temporal and vertical changes in temperature (°C) at forebay Station 210 in Hartwell Lake for 1993-1994

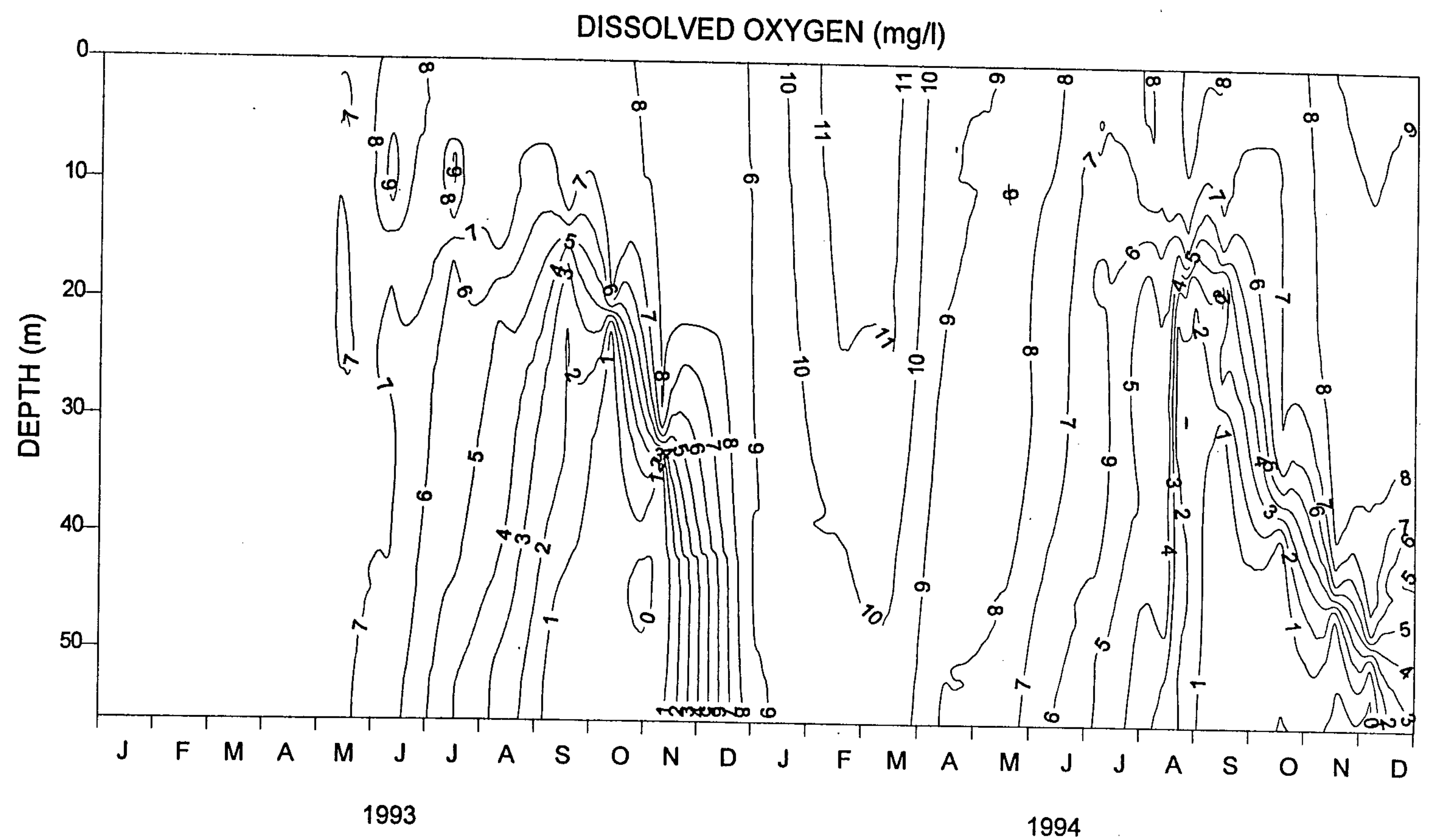


Figure 24. Temporal and vertical changes dissolved oxygen (mg/ℓ) at forebay Station 210 in Hartwell Lake for 1993-1994

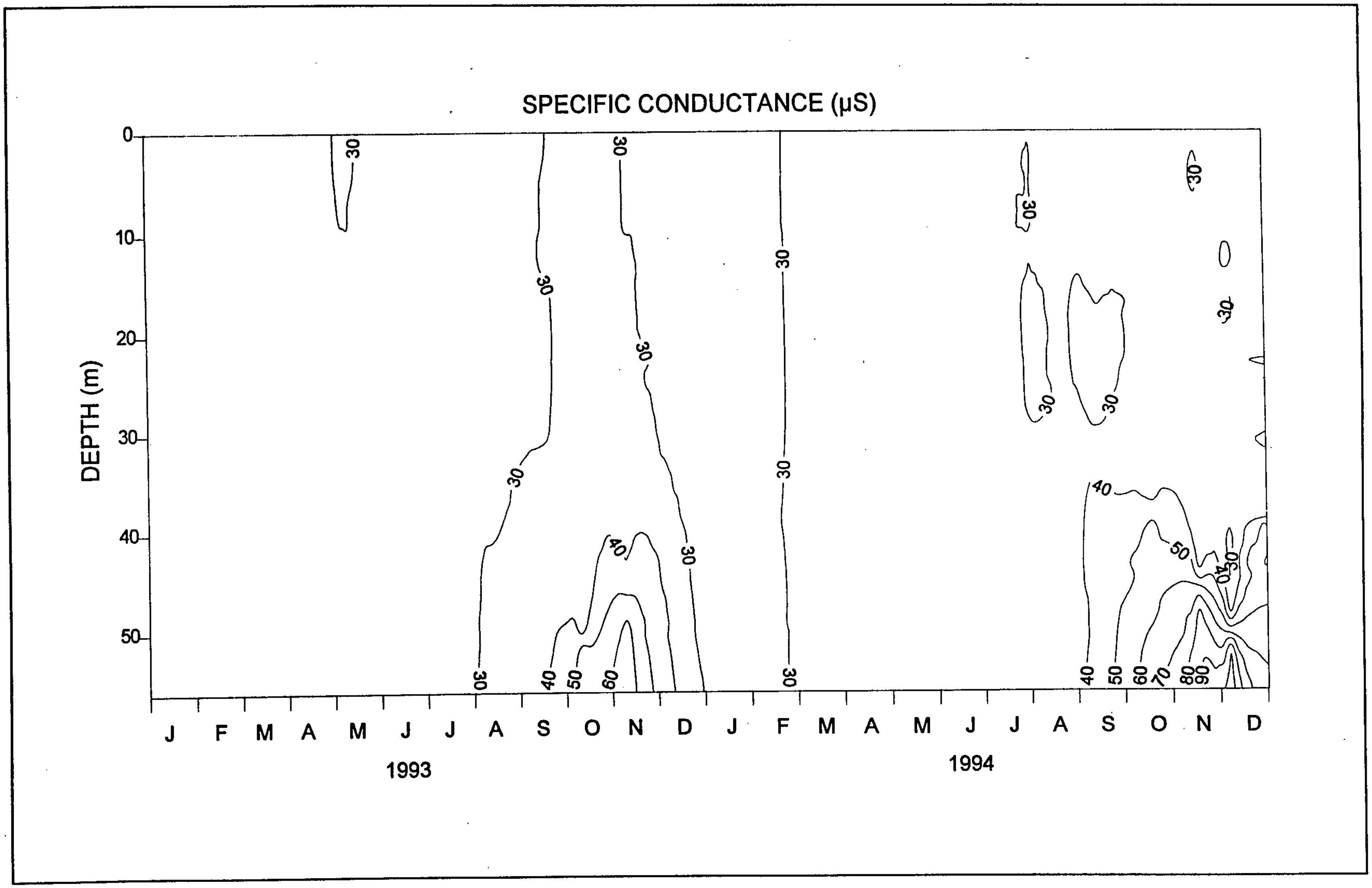
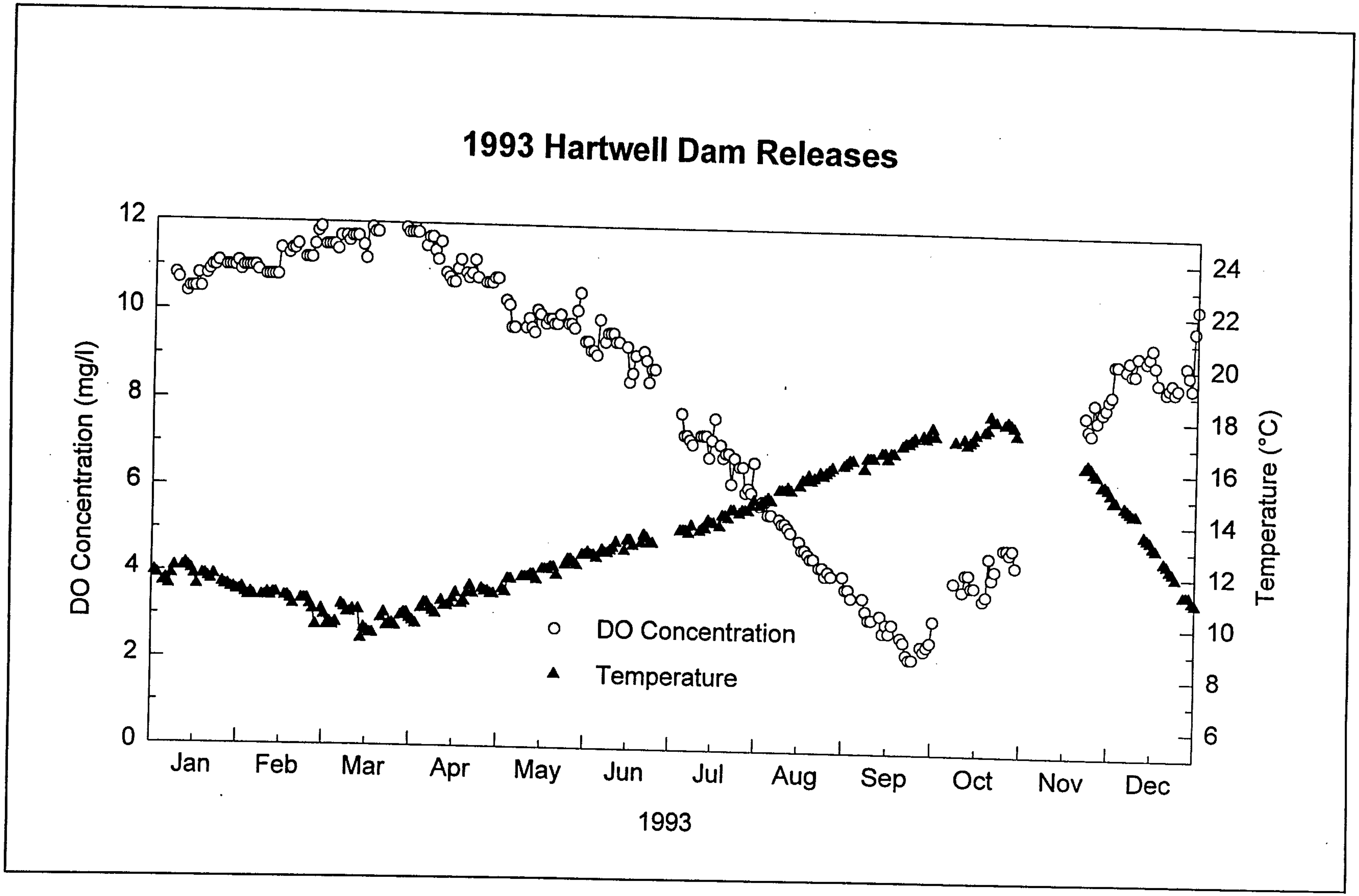


Figure 25. Temporal and vertical changes in specific conductance (μS) at forebay Station 210 in Hartwell Lake for 1993-1994



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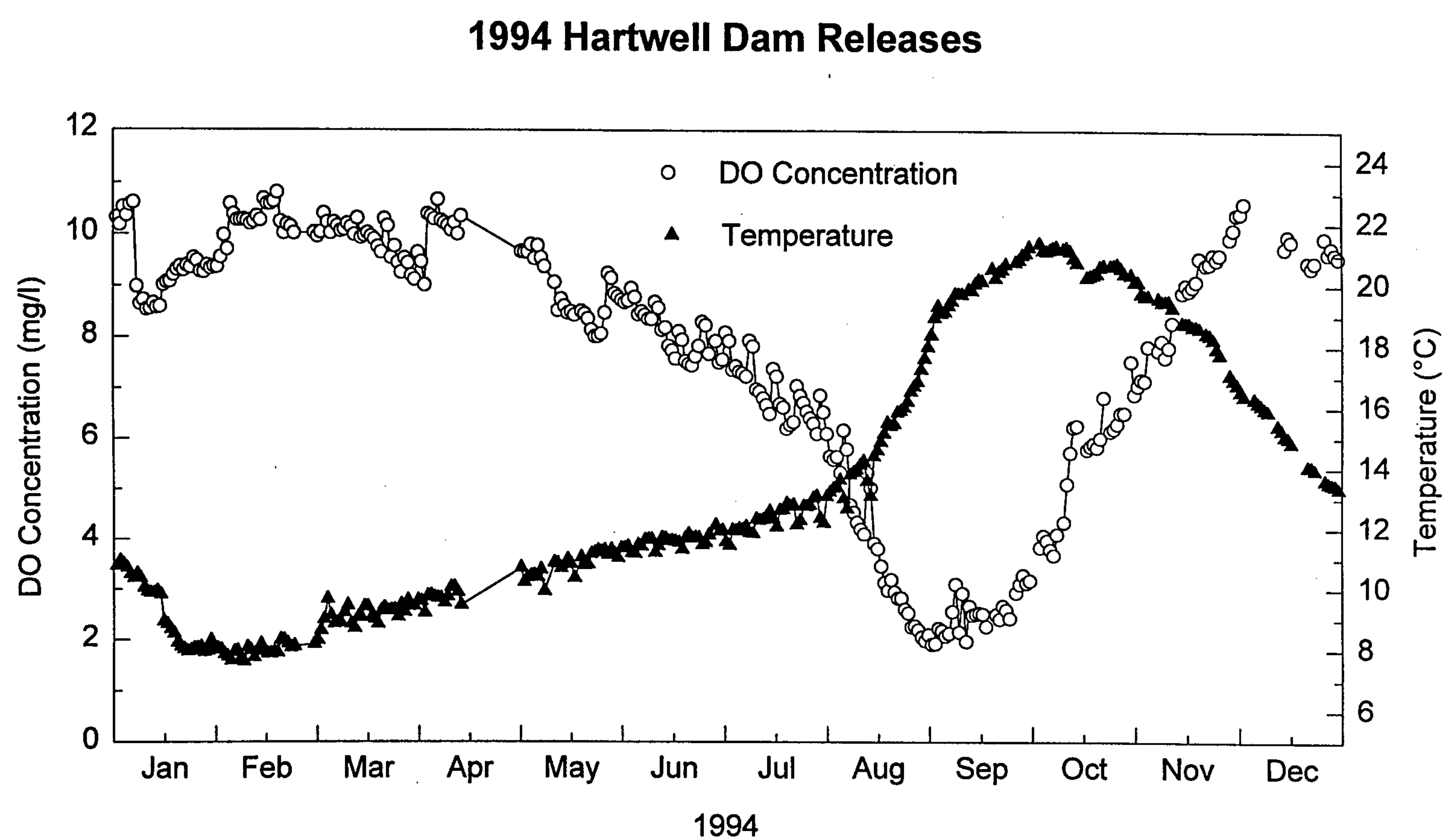

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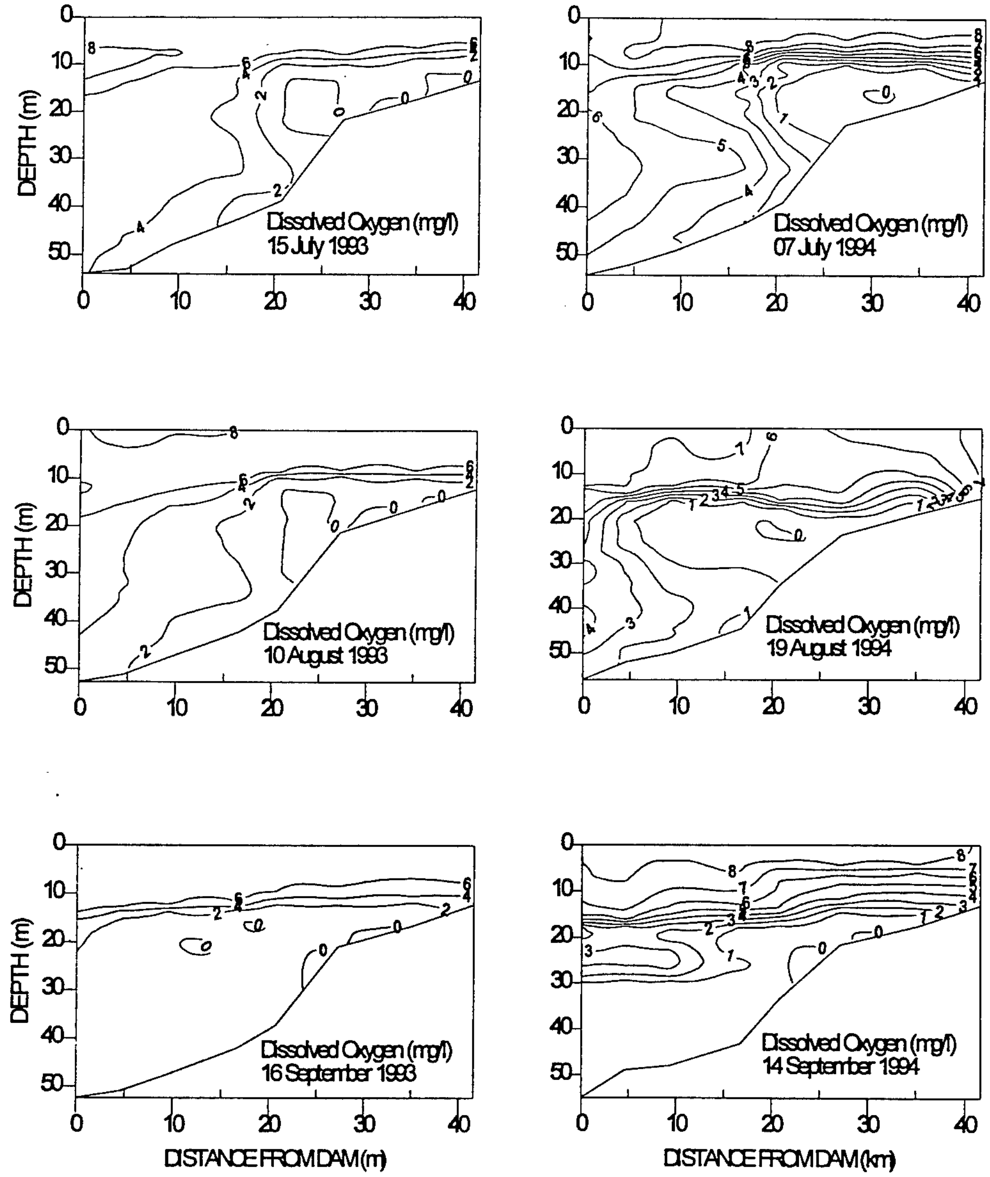

Figure 28. Spatial distribution of dissolved oxygen (mg/ℓ) from Hartwell Dam to upper Seneca River embayment for July, August, and September 1993-1994

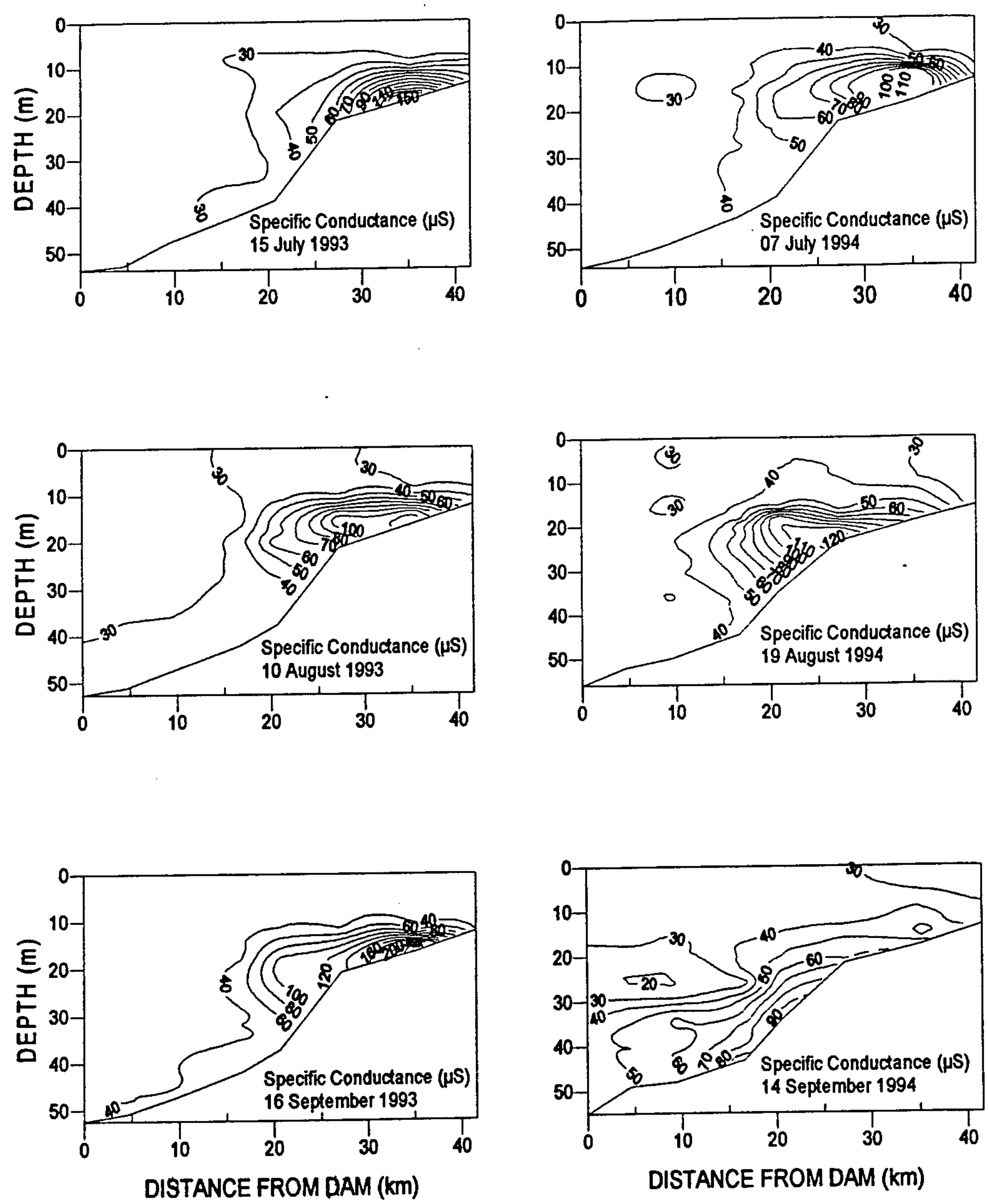

Figure 29. Spatial distribution of specific conductance (μS) from Hartwell Dam to upper Seneca River embayment for July, August, and September 1993-1994

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13. ABSTRACT *(Maximum 200 words)*

Hartwell (HW) Lake, completed in 1962, is a U.S. Army Corps of Engineers hydropower reservoir (surface area of 22,400 ha) located on the Savannah River on the Georgia/South Carolina border. HW Lake provides hydroelectric power production, flood control, water supply, and recreational usage.

In situ studies on HW Lake were conducted during 1993 and 1994 as part of an ongoing project describing temporal and spatial water quality patterns and trends on three Savannah River reservoirs. Temperature, dissolved oxygen (DO) concentration, pH, and specific conductance measurements were collected monthly from April 1993 through December 1994, with the exception of January 1994. HW tailrace data (temperature, DO, pH, and specific conductance) were collected hourly through the period via a remote monitor immediately downstream of HW Dam.

Water quality conditions on HW Lake were influenced by many factors during 1993 and 1994, including hydrology, climate, anoxia development, and loading processes. The greatest variability in DO concentration was observed in the Seneca River embayment stations farthest upstream. The onset and formation of anoxic conditions during early to midsummer directly impacted later summer forebay and release water quality during both years. Pronounced differences in DO and specific conductance patterns during 1993 and 1994 can be attributed to precipitation, inflow, and discharge effects.

14. SUBJECT TERMS

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